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FEASIBILITY DEVELOPMENT OF VARIABLE DEMAND LIQUID PROPELLANT GAS GENERATOR

by

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ABSTRACT. Theoretical and experimental studies were made to determine the feasibility of using a variable-demand liquid-propellant gas generator for pressurization of propellant tanks.

Operating principles and test results of two self-regulating variable-demand gas generators are presented. Red fuming nitric acid was successfully expelled by direct pressurization from a propellant tank at variable flow rates while maintaining a constant tank pressure. The results showed that a variable-demand liquid-bipropellant gas generator is feasible for a prepacked pressurization system.

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FOREWORD

Research and feasibility studies of the Packrat II variable-demand liquid-propellant gas generator were supported by propulsion research funds allocated for liquid-rocket research by the U. S. Naval Ordnance Test Station (NOTS).

Research and development of the 0-35-pound variable-demand liquid-propellant gas generator were supported by funds from Problem Assignment Number 2, WEPTASK RMMP-24 080/216-1/F009-06-02. A low level of effort was officially begun at NOTS on Packrat II gas generator in January 1960 and completed in July 1961, and on the 0-35-pound gas generator work was begun on 15 September 1961 and completed on 20 February 1963.

This report describes the research and preliminary experimental development of Packrat II and 0-35-pound gas generators. Brief descriptions of major components of the gas generators and their control systems are given in the body of this report, but a more detailed description of the two gas generators and propellant studies is presented in the appendixes.

This report was reviewed for technical accuracy by D. H. Couch, B. Glatt, and D. H. Strietzel.

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CONTENTS

Figures:

NOMENCLATURE

A_f	Fuel orifice area
$A_{ox.}$	Oxidizer orifice area
c^*	Characteristic exhaust velocity
C_{d_f}	Fuel orifice discharge coefficient
$C_{d_{ox.}}$	Oxidizer orifice discharge coefficient
C_f	Thrust coefficient
L^*	Characteristic length
O/F	Oxidizer to fuel ratio
ΔP	Pressure drop through injector
P_a	Ambient pressure
P_c	Combustion chamber pressure
P_e	Combustion chamber nozzle exit pressure
t_b	Total burning time
T_c	Combustion chamber temperature
T_e	Combustion chamber exit temperature
$\dot{W}_T$	Total propellant flow rate

INTRODUCTION

The present state-of-the-art technology for pressurizing most liquid-propellant tanks is through the use of cold gas stored at high pressure; however, the weight and volume of the cold gas system is excessive for a high-propellant mass function system. Liquid bipropellant gas generators have looked attractive for prepackaged liquid systems for some time. Some prepacked liquid-propulsion systems, such as the LAR and BULLPUP, have successfully used a solid-propellant gas generator for pressurization, but these applications were for short burn times and fixed-thrust levels. The more advanced propulsion system with requirements of variable thrust, pulse, on-off thrust, and long burning time requires a variable gas generator pressurization system; therefore, a liquid-propellant gas generator with variable gas generation rates is highly desirable in achieving low-system weights, and in meeting these design requirements with versatility.

The applications for a variable-demand liquid-propellant gas generator are unlimited. Some specific applications are: (1) the retro-propulsion system for lunar landing or simulators; (2) hovering instrumentation platforms; (3) maneuvering of space vehicles and satellites; (4) a gas driven turbo generator for a missile power-supply system; (5) a propellant pressurization system; and (6) for pitch, yaw, roll, and thrust-vector control of missiles.

The advantages in using a variable-demand liquid-propellant gas generator are: (1) provides variable gas generation rates upon demand; (2) maintains a constant gas pressure while completely utilizing all of the generated gases; (3) eliminates the need to exhaust gas to the atmosphere during periods of thrust termination, thereby saving propellant; (4) provides on-off or intermittent operation; (5) provides flexibility in packaging; and (6) is lightweight and has functional flexibility. A disadvantage is that this type of gas generator is relatively complex, therefore more expensive than other types.

In 1956, the U. S. Naval Ordnance Test Station (NOTS) first originated the idea of using a variable-area type of injector system for varying thrust to meet an operational requirement for an air-to-air missile system called Diamondback. A year later NOTS demonstrated the feasibility in a 0-5,000-pound thrust motor using the variable-area injector principle. In 1959, this Station provided a liquid-propellant high-altitude target rocket for flight-evaluation testing of Sidewinder with a 50-300-pound variable-thrust motor, and in January of 1960, NOTS was funded to provide a variable-thrust propulsion system for an Army missile system Automet Missile A. At that time, a low level of effort was begun to study the various problems of a liquid-bipropellant variable-demand gas generator.

GENERAL DESCRIPTION

This report is broken down into two main divisions, a main body and three appendixes. The main body is written for general information only and the appendixes are written with detailed information for the design engineer who may wish to design variable-demand liquid-propellant gas generators or who may wish to continue experimental work to obtain more information.

A gas generator was developed as a pressurization system for Packrat II (Fig. 1), a 2,000-2,500-pound variable-thrust booster motor with a total propellant weight of 2,000 pounds of red fuming nitric acid (RFNA) and unsymmetrical dimethylhydrazine (UDMH); burning time of 26 seconds; and four fixed-position variable-thrust motors. The Packrat II booster motor was an experimental storable liquid-propellant motor, 24 inches in diameter by 130 inches in length. It was a backup for a solid-propellant NOTS air-launched space-booster motor and offered a wide range of thrust levels. Each of the four thrust chambers was canted 3 degrees and contained a small variable-area injector inside a fixed injector. The variable-area injector was actuated by a servovalve, thereby making it possible to control each thrust chamber separately, in pairs, or all four simultaneously. It offered the possibilities of programming a desired thrust-time curve, and control of pitch, yaw, and roll, if desired.

The propellant combination of RFNA and UDMH for the Packrat II gas generator was selected to first investigate a gas generator system using the same propellants that were contained in the booster motor to be pressurized, and to minimize the reaction between the hot gases and the propellants when directly pressurized.

The increasing demand for a hot-gas-pressurization system with flexibility in packaging, fast response, restart capability, short and long duration burning, complete utilization of generated gases, light weight, and low hot-gas temperatures led to the initiation of a research and experimental feasibility development program of the 0-35-pound gas generator at NOTS.

The gas generator was called 0-35-pound because the injector assembly with electro-hydraulic control system was designed to be used as both a variable-demand gas generator and 0-35-pound variable-thrust motor. The latter would require some modifications on the pintle and orifice seat areas before it could be used as a 0-35-pound variable-thrust motor.

The propellant selection of RFNA and UDMH for the 0-35-pound gas generator was made because of availability and NOTS experience with it, coupled with good chemical and physical properties. This propellant was not intended to be the ultimate propellant combination

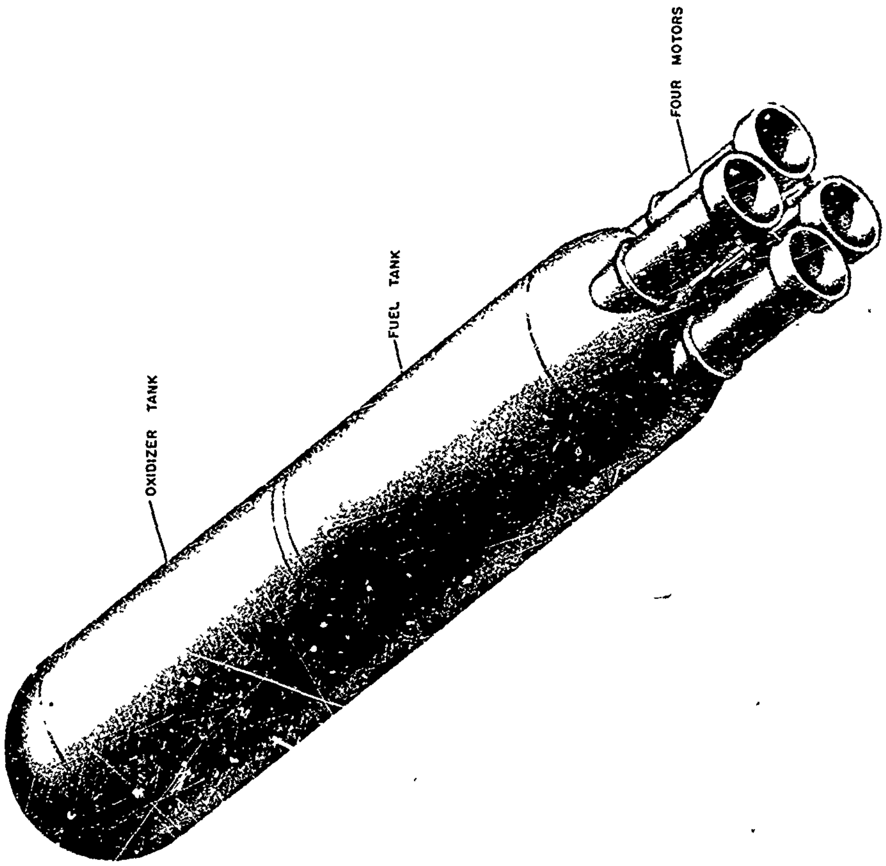


FIG. 1. Packrat II Booster Motor.

for the gas generator, but was only intended to be used in proving out the feasibility of the variable-demand liquid-propellant gas generator control system. Simultaneous with this feasibility development, a propellant study was independently conducted to optimize propellant for these applications and provide data for future applications. A literature search revealed that no work had been reported with pre-packaged bipropellant variable-demand liquid-propellant gas generators and that very few theoretical or experimental performance data on storable gas generator propellants were available. Therefore, an extensive program to obtain basic theoretical propellant and variable-demand gas generator performance data was initiated (Ref. 1-4).

PROPELLANT STUDIES

THEORETICAL PROPELLANT STUDIES

The performance of several propellant combinations suitable for use in a bipropellant gas generator and their theoretical combustion temperatures were calculated. Figure 2 is a plot of combustion temperatures versus oxidizer-to-fuel (O/F) ratios for some of the propellants that had the lowest theoretical combustion temperatures.

It was theoretically indicated that 95% ammonia and 5% lithium hydroxide, or ethyl alcohol with red fuming nitric acid would provide the desired low-flame temperatures. Among the different fuels with RFNA (oxidizer), 95% ammonia and 5% lithium hydroxide (LiOH), fuel rich and MHF-3 oxidizer rich with RFNA had the lowest theoretical combustion temperature.

Additional theoretical data are described in Appendix A for those propellant combinations that were investigated, but after running preliminary calculations at O/F ratios of 1:1, they did not look as promising as was expected. Additional theoretical propellant calculations were run for both oxidizer and fuel rich cases for the most promising propellants shown in Table 2 Appendix A.

EXPERIMENTAL PROPELLANT STUDIES

Preliminary experimental propellant tests were made before designing the 0-35-pound gas generator. Several evaluation tests to study the ignition and combustion of IRFNA and UDMH at O/F ratios down to 0.2 were made with a test apparatus called Micromix. Four methods shown in Appendix A were employed in obtaining the temperatures and the test results of the Micromix studies. The experimental data obtained from these tests were used in determining the O/F ratio for the 0-35-pound gas generator injector and the L^* to be used for a water-cooled combustion chamber.

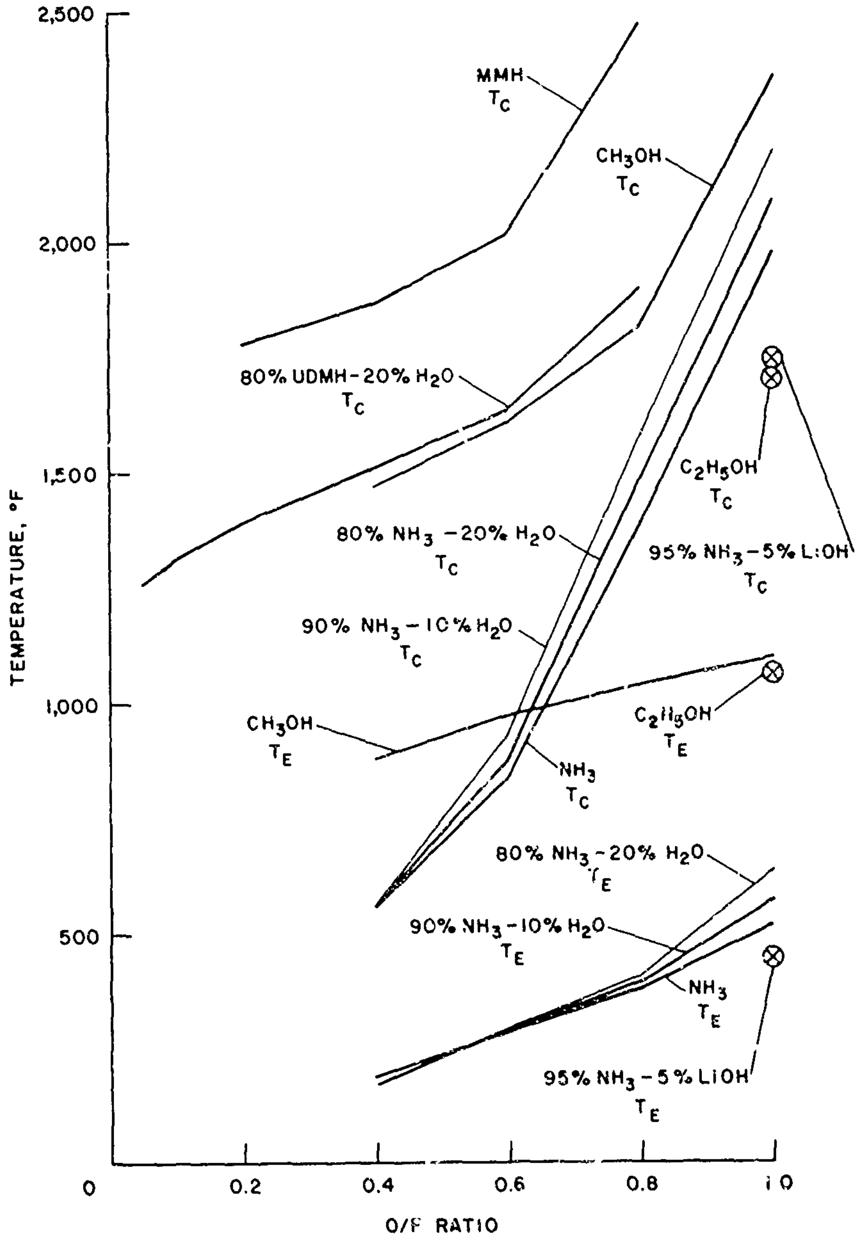


FIG. 2. Theoretical Calculations of RFNA (14% NO_2) With Selected Fuels at 700 psia Chamber Pressure.

The experimental work done on the 0-35-pound gas generator used various combinations of RFNA/UDMH and RFNA/80% UDMH-20% H_2O by weight. Figures 3 and 4 show a comparison of the theoretical versus experimental data of these propellant combinations.

Figure 3 compares the experimental temperatures of the combustion gas as a function of mixture ratio with the theoretical calculations. The experimental temperatures for the 80% UDMH-20%H_2O system were within the theoretical temperatures by 20 to 50°F lower, while the straight UDMH experimental temperatures were lower than the theoretical temperatures in the low mixture ratios of 0.4 by 150°F, by 20°F in the middle O/F range of 0.7, and by 150°F in the higher mixture ratios of 1.0

Figure 4 shows the theoretical versus experimental combustion performance of c^*. The experimental c^* for both RFNA/UDMH and RFNA/80% UDMH-20% H_2O were lower by 1,300 to 1,700 ft/sec than the theoretical c^*. The low c^* may be due to the fact that a longer L^* than the 250 inches used is required for more efficient combustion when using water-diluted UDMH.

GAS GENERATOR DESIGN STUDIES

PRESSURIZATION SYSTEMS STUDIES

An extensive comparison study of pressurization systems for Packrat II Booster Motor and the Condor missile was made comparing weights, sizes, and propellant weight fractions (Fig. 5-8). The Condor missile is an air-to-ground guided missile requiring a variable-thrust propulsion motor with stop and start capability. The Packrat II gas generator, and the 0-35-pound gas generator for the Condor missile proved to be the most favorable pressurization systems.

The design studies were concentrated in three individual areas of effort: the injector, combustion chamber, and control system (Ref. 5-6). As a result of the study, basic designs of experimental units including two injector assembly configurations, one combustion chamber assembly, and three control systems were established, and are described herein as static-test hardware for the two different applications.

A study was made on an alternate control system for a liquid-propellant gas generator with a centromix injector and a mechanical feedback control. A hot-gas-controlled bipropellant injector valve was designed and fabricated to meet the Condor missile pressurization requirements. No hot firing tests were conducted. Table 1 shows the different gas generator physical design characteristics studied.

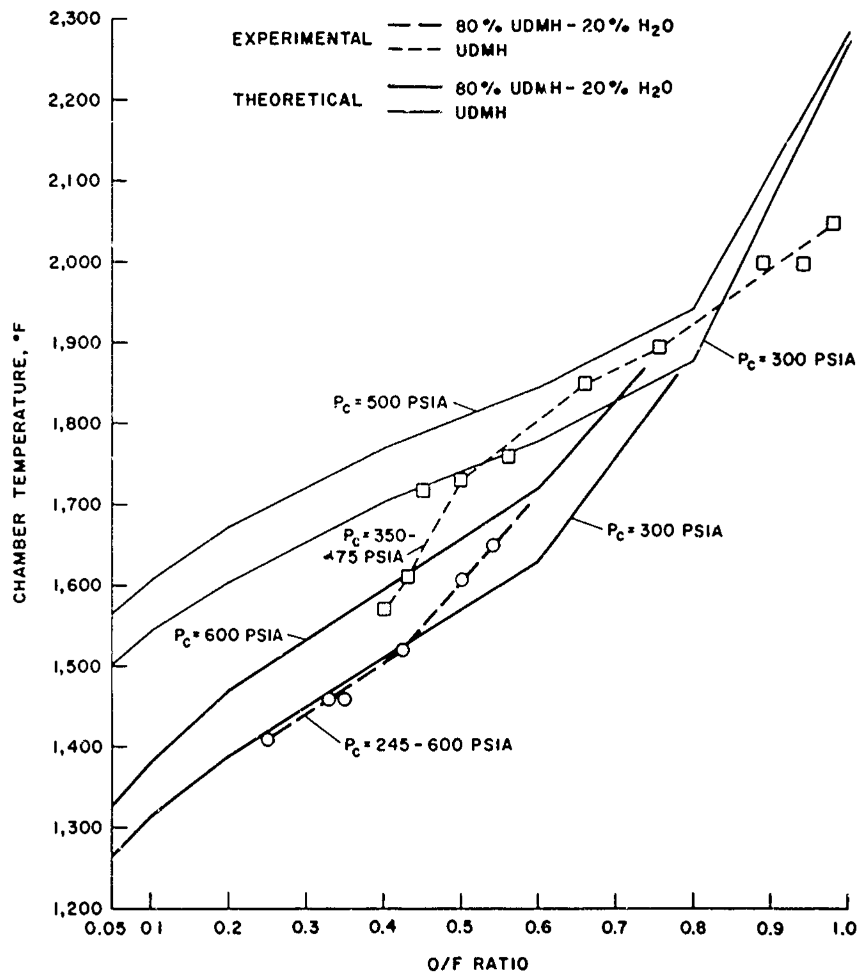


FIG. 3. Theoretical Versus Experimental Propellant Performance of RFNA (14% NO_2) With Various Mixtures of Fuels at 300 to 600 psia Chamber Pressure.

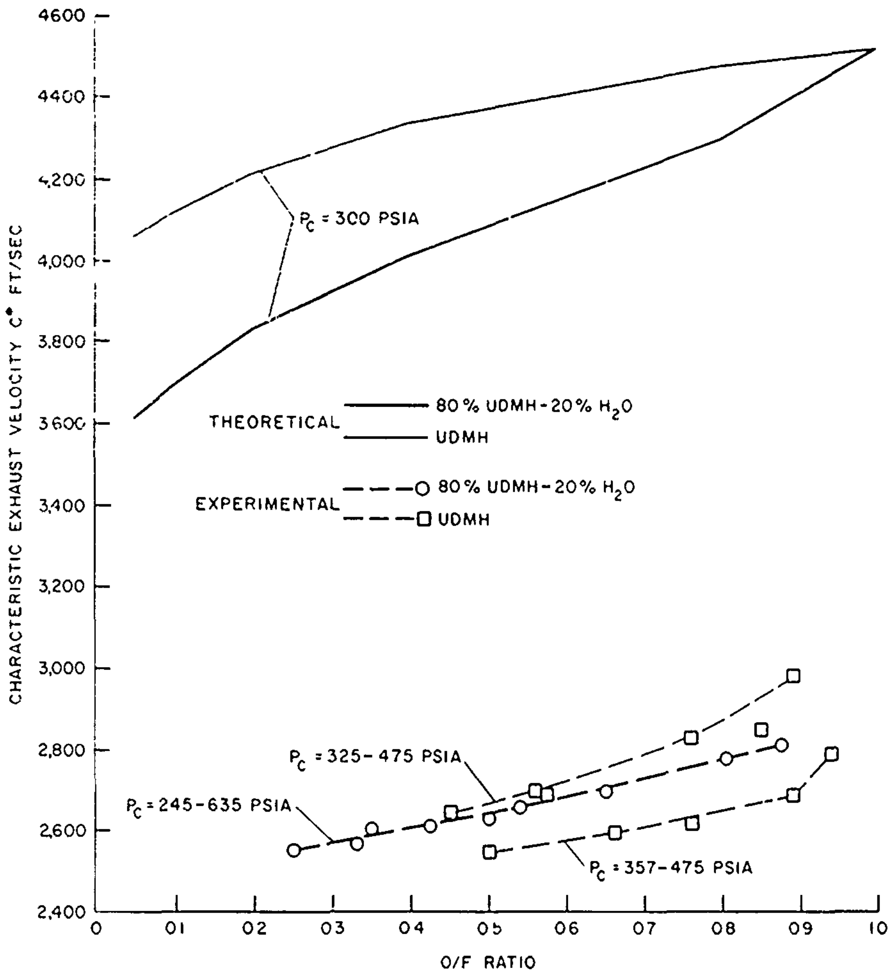
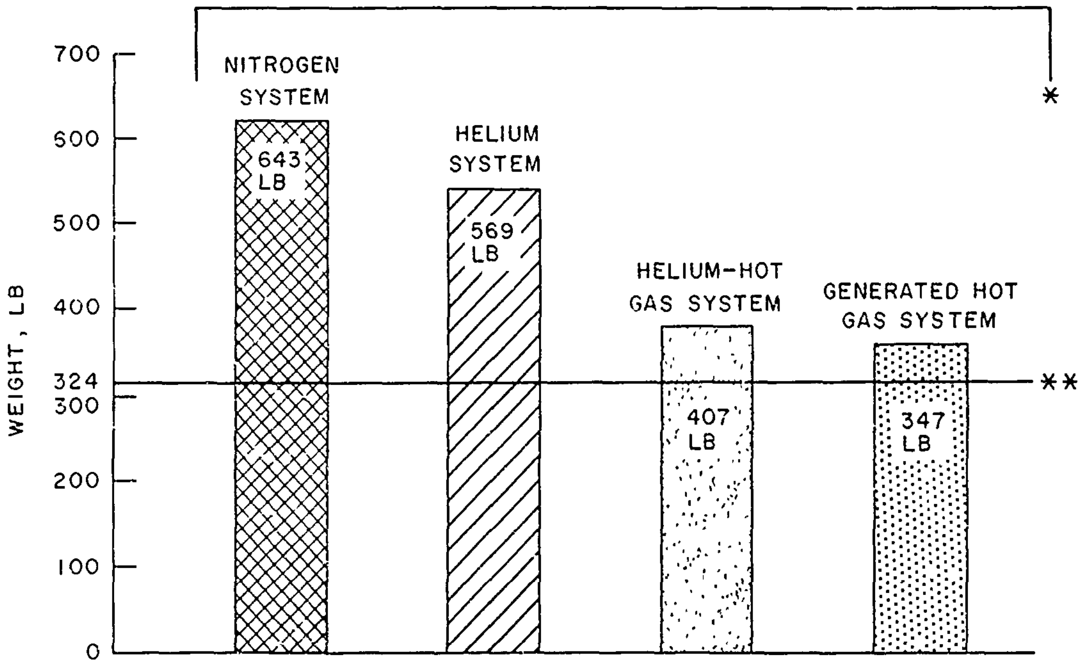


FIG. 4. Theoretical Versus Experimental c* of RFNA (14% NO_2, 1.5% H_2O) With UDMH and 80% UDMH-20% H_2O.



* INERT HARDWARE WEIGHT INCLUDING PRESSURIZATION SYSTEM WEIGHT

** INERT HARDWARE WEIGHT EXCLUDING PRESSURIZATION SYSTEM WEIGHT

FIG. 5. Weight Comparisons of Pressurization Systems for Packrat II Booster Motor.

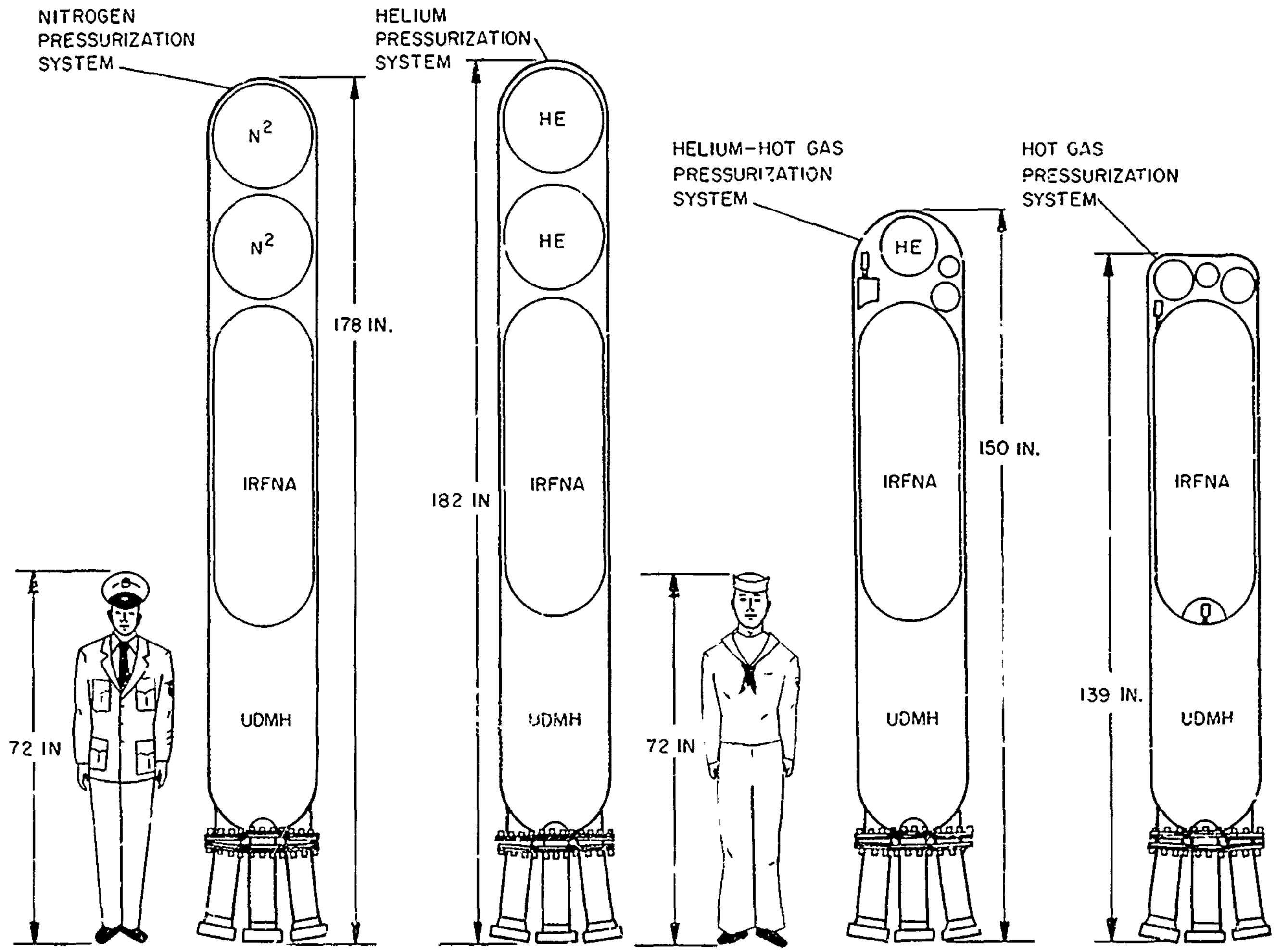


FIG. 6. Size Comparisons of Fackrat II Booster Motor.

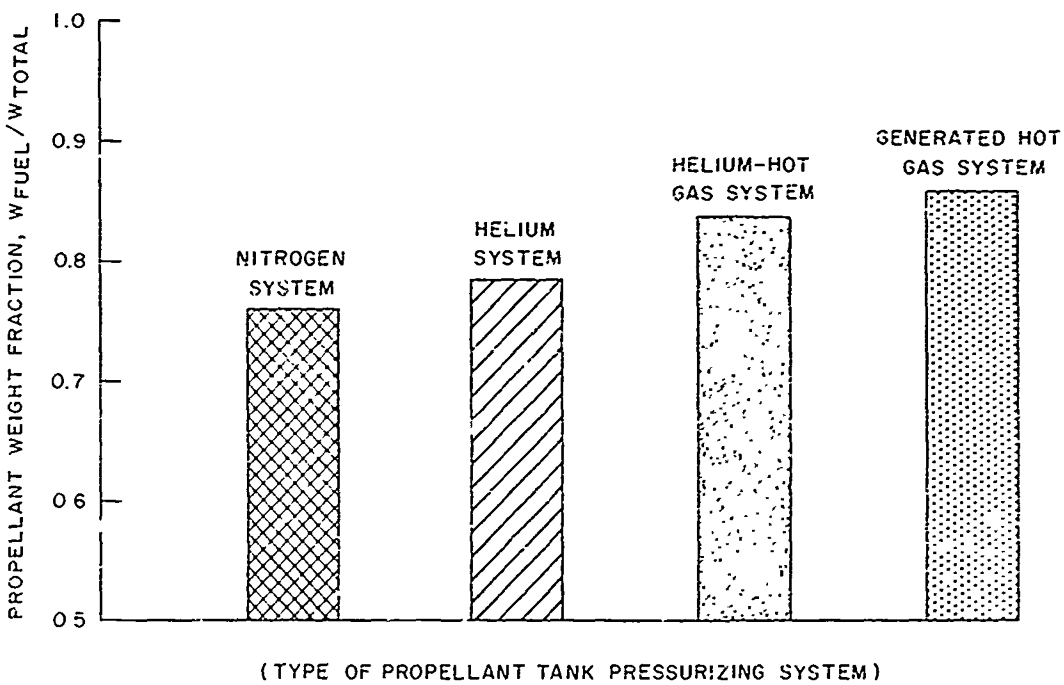


FIG. 7. Comparison of Propellant Weight Fraction for Packrat II Booster Motor.

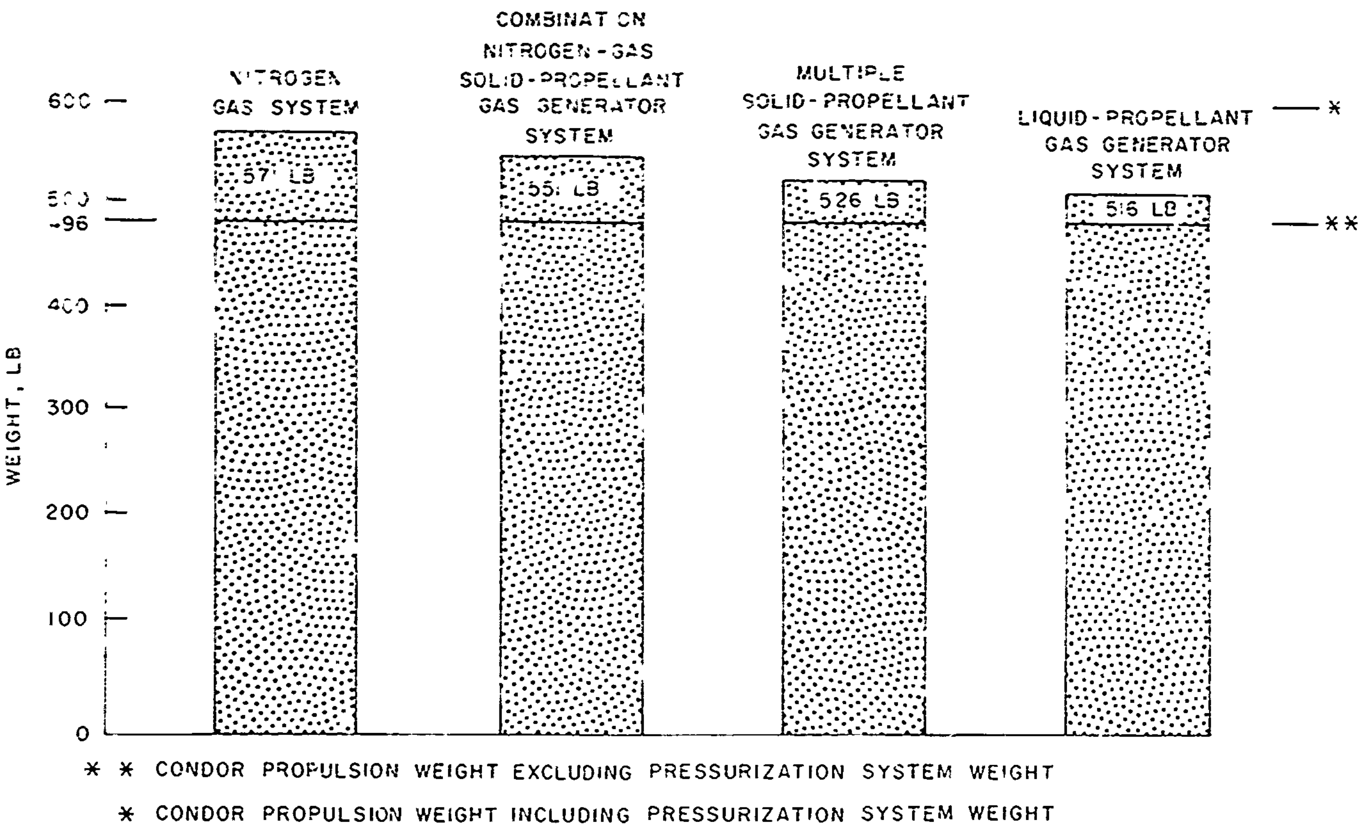


FIG. 8. Weight Comparisons of Pressurization Systems for Condor Motor.

TABLE 1. Gas Generator Physical Design Characteristics

Characteristic	Packrat II, variable area, RFNA/UDMH	0-35-lb, variable area, RFNA/80% UDMH-20% H_2O by weight	Condor, bipropellant injector valve, RFNA/80% UDMH-20% H_2O by weight
A. Injector Parameters[a]			
$\dot{W}$, lb/sec	0.737	0.170	0.026
O/F	10:1	0.48:1	0.5:1
ΔP, psi	150	150	150
Pintle travel, in.	0.0155	0.025	---
A_{ox}, in^2	0.0098	0.0016	0.000151
A_f, in^2	0.00134	0.00226	0.000423
$C_{d_{ox}}$	0.75	0.75	0.7
C_{d_f}	0.75	0.75	0.7
Control system	Self pressure regulated by generated gas pressure acting on diaphragm	Pressure feedback control using a pressure transducer	Self pressure regulated by generated gas pressure acting on feedback piston
Pintle actuation area, in^2	---	0.250	---
(diaphragm)	1.8415	---	---
B. Water Cooled Combustion Chamber With Copper Liner and Stainless Steel Jacket			
L^*, in.	---	250	---
Designed P_c, psi	---	600	---
C_f	---	1.267	---

[a]Material of Packrat II and Condor injectors: stainless steel.

PACKRAT II GAS GENERATOR

During the feasibility development program of a prepackaged storable booster motor Packrat II, there was a requirement for a hypergolic bipropellant liquid-propellant gas generator using RFNA/UDMH as the propellants and with a variable-area-demand injector. The generator was to provide pressurization for various demands imposed by the changing modes of operation of the main variable-demand liquid-propellant booster motor.

All of the work performed on the Packrat II gas generator program had been directed to perfecting the variable-demand liquid-propellant injector preparatory to using it to directly pressurize red fuming nitric acid in an experimental expulsion tank, expelling it at various flow rates.

In order to evaluate the gas generator injector design characteristics and the mechanical feedback control system, water tests were conducted with the injector, and nitrogen (for the sake of simplicity) was used for controlling the pintle positions.

During the Packrat II gas generator program, a series of successful gas generator static tests were conducted which indicated that the self-pressure-regulating gas generator could respond to a wide range of recorded generation flow rates from 0 to .500 pound per second. The self-pressure-regulating control system provided smooth combustion throughout each run while maintaining a constant combustion pressure from 0 to 500 psig at each control pressure setting, and operating at RFNA to UDMH (O/F) ratios in the range of 3:1 to 10.7:1.

Two acid expulsion tests were conducted on directly pressurizing a tank filled with 129 pounds of RFNA (oxidizer) and running the gas generator at an O/F ratio of approximately 10:1 to 10.5:1 for 30 seconds each. Although the tank configuration permitted direct contact of the generated gas with the liquid surface (a limited chemical reaction occurred) the maximum recorded temperature above the liquid-gas interface did not exceed 245°F.

The gas generator withstood a total of 20 long-duration firings at various burning times up to a maximum of 50 seconds. The total burning time accumulated with this injector was over 12 minutes for the entire development program.

The Packrat II gas generator, including injector assembly and control system, and the tests conducted are described in more detail in Appendix B.

0-35-POUND GAS GENERATOR

The propellant combination selected for the 0-35-pound gas generator application was RFNA and UDMH. This selection was based on the following considerations:

1. Availability

2. Experience: the ordnance personnel at NOTS had eight to nine years of experience in handling, storage, and firing these propellants. This propellant combination has proved an old reliable "work horse" storable propellant by NOTS, because of its long record of reliable performance, easy adaptability, and good physical characteristics.

3. Chemical properties: the combination is hypergolic over a wide range of conditions; these include UDMH as a diluent with 20% to 30% water mixed with it, or straight UDMH as a diluent at O/F ratios of 0.2:1 to 1.0:1.0. They require no ignition system for either initial start or subsequent restarts, even at these low fuel rich O/F ratios. Unless a large fuel leadtime occurs, starts are smooth. The low molecular weight and chamber and exhaust temperatures were also considered.

4. Physical properties: the RFNA-UDMH system offers exceptionally good physical properties in terms of storage life, allowable temperature limits, and system density. Rockets containing straight IRFNA-UDMH have been stored at NOTS for up to eight years at ambient temperature, and up to three years at 165°F, with no apparent damage from corrosion or decomposition. The relatively high bulk density provides for lower propellant tank weight and a more compact system.

All test work on the 0-35-pound gas generator had been done in perfecting the variable-demand liquid gas generator preparatory to using it to pressurize a metal collapsible propellant tank system in an actual hot firing of a liquid propellant motor.

In order to evaluate the gas generator design characteristics and electro-hydraulic servo control system, hydraulic bench tests were conducted in the servo laboratory. Almost all of the investigation was carried out using feedback from a linear-position transducer attached to the pintle. Some investigation was carried out using feedback from a chamber pressure transducer, but it was felt that a hot firing would be best in proving out this feedback control system. The injector used for the 0-35-pound gas generator is classified as a ribbon injector, because of the injection pattern. Oxidizer and fuel are metered and injected through opposing slots. The oxidizer and fuel ribbon stream impinges, thus mixing. This method of injection is used for this size of hypergolic gas generator because of the small propellant flows.

The injector utilizes a positioning pintle. Metering of the propellants is accomplished by metering the pintle. The pintle face has a sharp edge on both fuel and oxidizer orifices. The fuel is fed through the outer orifice of the pintle, and oxidizer is fed through the center orifice of the pintle. The sharp edges of the fuel and oxidizer orifice face, on the pintle, meters the propellant as it passes over the injection slots. A change in the pintle position causes a proportional change in the propellant flow rates. The sharp edge of the pintle face bottoms in a conical seat providing zero leakage of propellants into the combustion chamber in the closed or off position. The pintle position can be controlled by either pintle position feedback, or tank or chamber pressure feedback.

Seven static firings were made to demonstrate the feasibility of the gas generator control system. The control system was set up so that either pintle position or combustion chamber pressure feedback signals could be obtained from them.

In the first test a linear displacement transducer which measured pintle position was used to provide the feedback signal. The gas generator responded very successfully to all input commands at various pintle position settings, and ignition was hypergolic and combustion was smooth throughout the entire 30-second run. After demonstrating pintle position feedback control, the control system was switched to receive the feedback signal from a combustion chamber pressure transducer.

All but the first of these six test series functioned properly for command inputs. They stabilized at the command pressures and remained constant at the various pressure levels. The only failure was due to a minor problem in the chamber-pressure transducer feedback line. Otherwise, in all of these 30-second duration tests ignition was hypergolic and combustion smooth throughout the firings. Figure 9 shows the combustion performance for the last three tests, and compares the experimental constant gas generator pressures for chamber pressures of 325, 500, and 600 psia as a function of burning time versus chamber pressure and temperature. It also shows that the gas generator for these predetermined chamber pressures can be controlled within ±10 psi. The total accumulated burning time with this gas generator injector was over 3 1/2 minutes.

Appendix C describes in more detail all of the test work done on the 0-35-pound gas generator.

CONDOR GAS GENERATOR CONTROL SYSTEM

The hot gas controlled bipropellant injector valve (Fig. 10) was intended to be not only an advanced alternate gas generator control

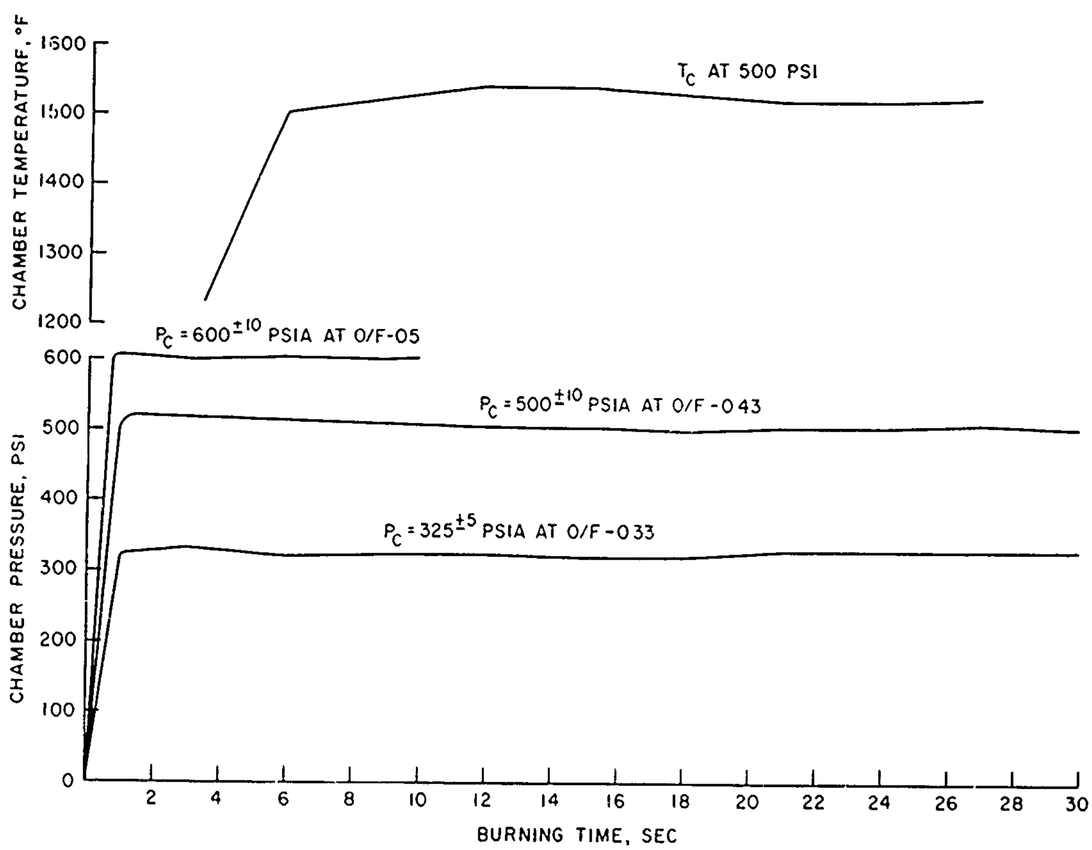


FIG. 9. Experimental Constant Gas Generation Pressures for P_C of 325, 500, and 600 psia Using RFNA (14% NO_2, 1.5% H_2O)/80% UDMH-20% H_2O

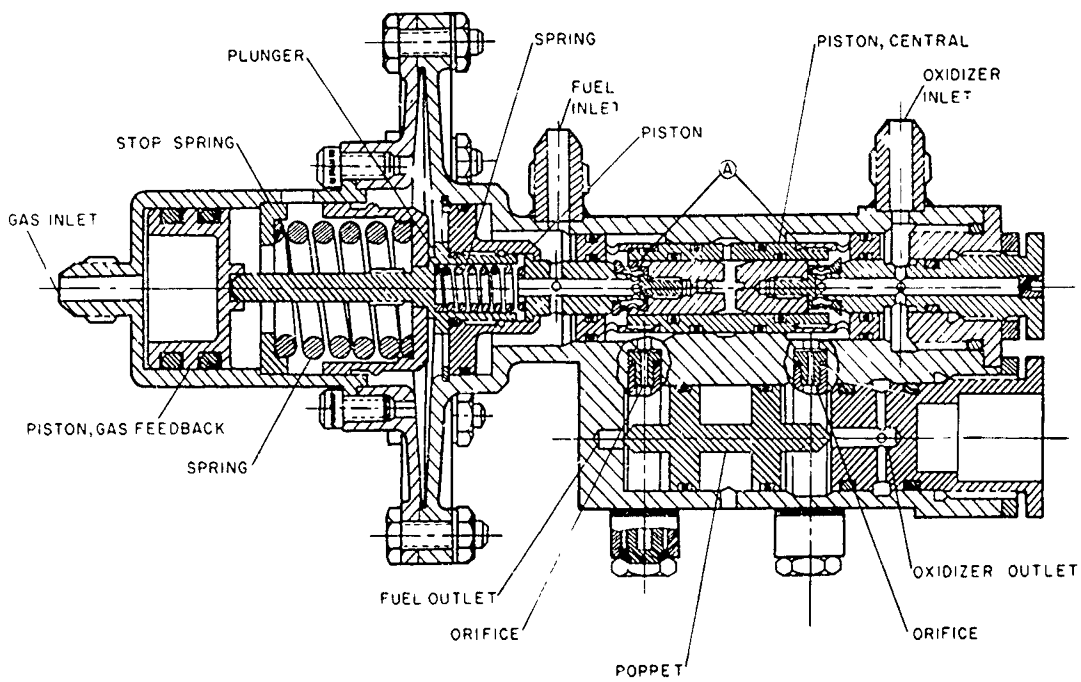


FIG. 10. Hot Gas Controlled Bipropellant Injector-Valve Assembly.

system, but was designed to ultimately be used with a centromix injector as part of a gas generator pressurization system for the Condor missile. Figure 11 shows the valve hardware.

This valve was also to be used initially for preparatory gas generator studies on propellants. The valve allows ready adjustment of the O/F ratio by changing the orifices and centromix injectors for particular propellant combinations. Figure 12 shows a diagram of the control system.

Figure 10 shows the detailed components of the Condor valve. It operates in the following manner: the fuel enters the unit and pushes the piston to the left when the pressure exceeds the preload on the spring: this pulls the piston and poppet group to the right, allowing flow to begin at the metering poppets A. Note that the spring prevents the poppets from premature opening during the interval when pressure is not sufficient to open the poppets A and B.

Once flow begins through poppet A, any difference in outlet pressure between the oxidizer and fuel systems is compensated for by the central piston which is free to move in either direction and modulate the pressures until they are equal. This means that the pressures seen by the orifices are equal on both the oxidizer and fuel sides. Flow then proceeds to the equalizing valve poppet which maintains equal pressures on the downstream side of the orifices. This gives a constant O/F ratio with no O/F shifting.

Shut-off begins when the gas feedback piston is driven to the left by the combustion gas pressure from the chamber or main propellant tank. This exerts a force on the plunger which is coupled with the force on the spring and resisted by the force on the stop spring. When the combined gas pressure and spring preload loads are at a point where they are in equilibrium with the fuel pressure and stop spring force, the poppet and piston group snaps to the left, shutting off both fuel and oxidizer. Thus, the combustion pressure is always lower than the oxidizer/fuel pressure by an amount proportional to the spring preload.

Preliminary laboratory tests have been conducted to check out some of the design characteristics of the valve, and have shown a response time from full closed to open of 15 to 20 ms. No further work has been done with this valve.

CONCLUSIONS

1. It was determined, from the theoretical propellant calculations, that the desired temperature range of 1000 – 1200°F or less was

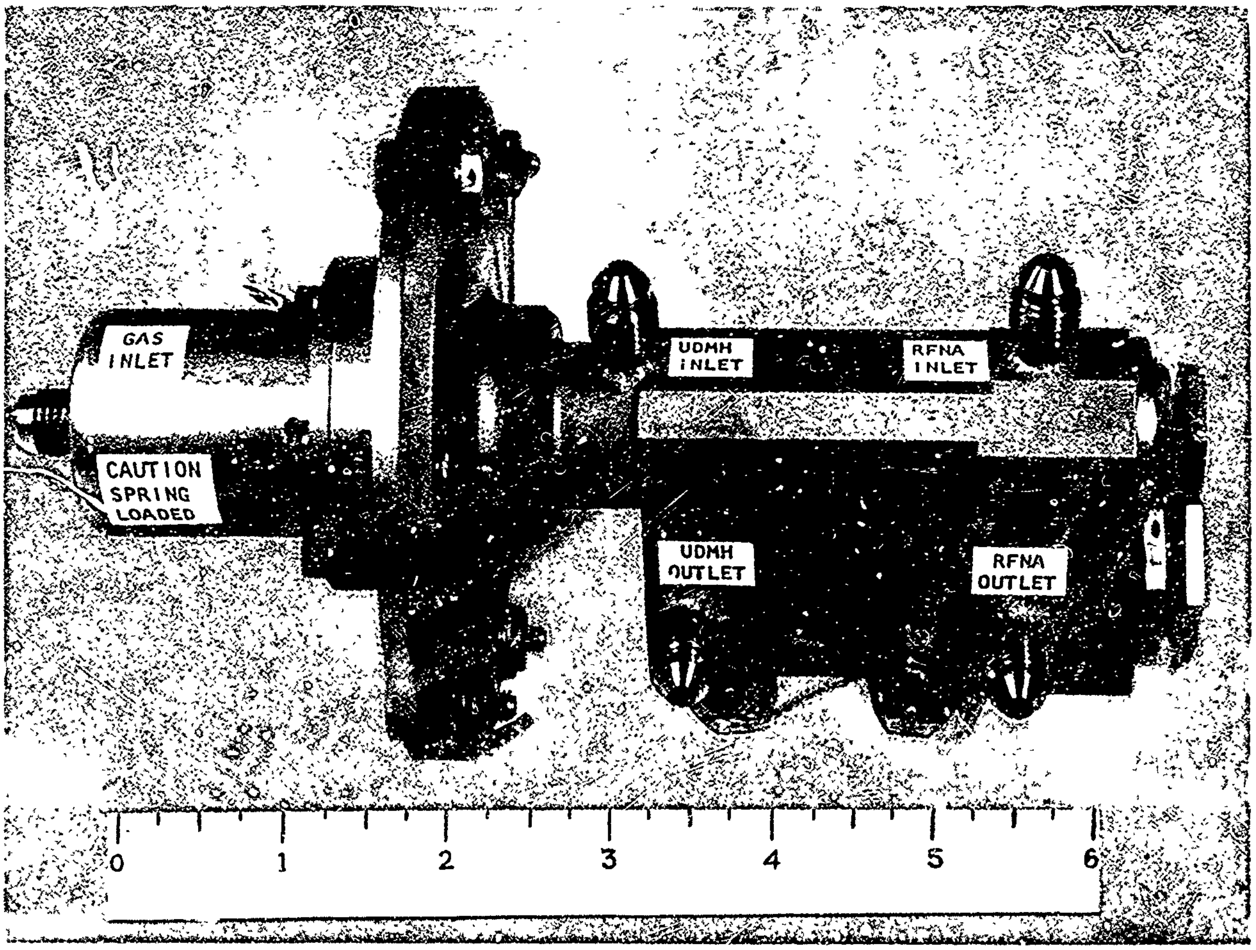


FIG. 11. Hot Gas-Controlled Bipropellant Injector-Valve Assembly Hardware.

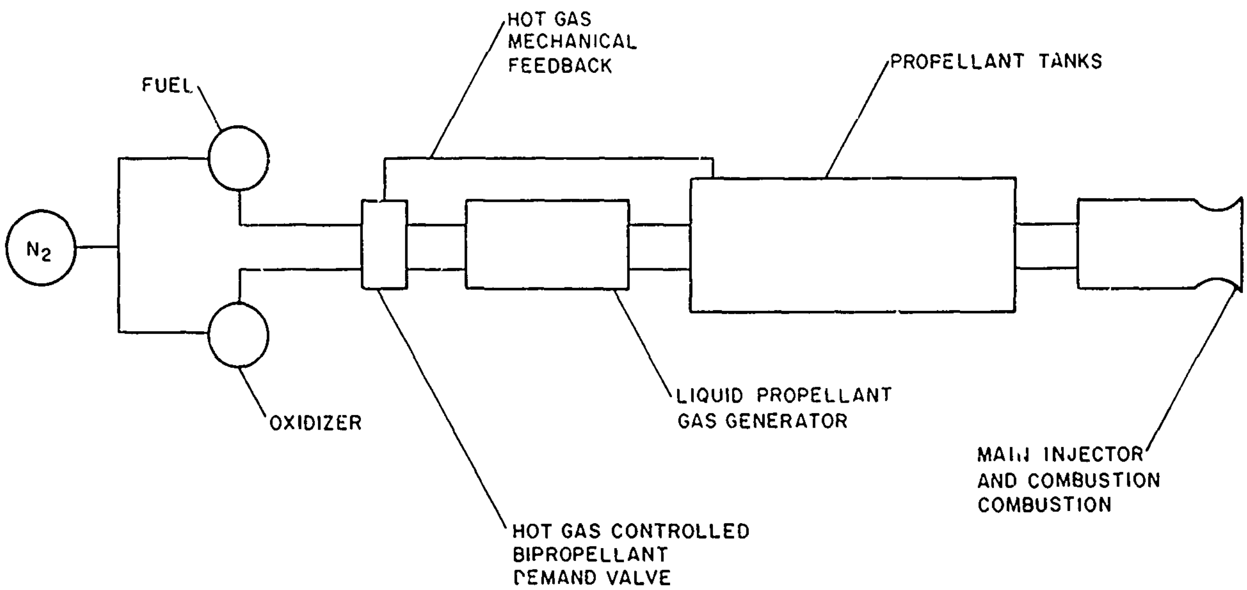


FIG. 12. Diagram of Condor Control System.

possible with either an oxidizer or a fuel rich mixture and in most cases have a storable hypergolic gas generator propellant.

2. In the Micromix experimental propellant studies and in the 0-35-pound gas generator fuel-rich static tests, it was determined that IRFNA/UDMH, RFNA/UDMH, and RFNA/80% UDMH-20% H_2O would provide hypergolic ignition and stable combustion over a wide O/F mixture range of 0.3:1 to 1:1.

3. The experimental tests showed that the addition of a certain percentage of water to UDMH by weight of the total propellants lowered the combustion temperatures by 300 to 500°F and still was hypergolic.

4. A combustion chamber with an L^* greater than 70 is required for thorough mixing of propellants and stable combustion when an O/F fuel or oxidizer rich mixture ratio of 0.3:1 to 20:1 is used.

5. A combustion chamber L^* of 250 to 400 inches is required when using an O/F ratio of 0.3:1 to 1:1 for IRFNA/UDMH, RFNA/UDMH, and RFNA/UDMH with 10% to 30% of water added by volume or weight to UDMH.

6. The information obtained from theoretical and experimental tests for both self-regulating variable-demand gas generators was extremely valuable in proving the feasibility of a storable prepackaged hypergolic bipropellant self-regulating variable-demand liquid-propellant gas generator as a pressurization system with restart capabilities and long-time operation.

7. Although there were no nitrogen and propellant tanks and uncooled combustion chambers designed for both gas generators, it was concluded that this would not impose a major problem in a development program; in most cases the combustion chamber would be a major problem, but in this case maximum combustion temperatures would be below 1200°F.

8. Packrat II gas generator proved the feasibility of a bipropellant variable-demand liquid-propellant gas generator when directly pressurizing a tank filled with RFNA and expelling the RFNA at various flow rates while maintaining a constant tank pressure.

9. The Packrat II gas generator proved its ability to operate at a wide range of oxidizer rich O/F ratios 3:1 to 10.7:1, while maintaining a constant combustion pressure from 0 to 500 ± 15 psi. Hypergolic ignition and smooth combustion were obtained throughout the entire test.

10. The more linear the ratio of chamber pressure to hydraulic pressure, the greater the response, and the better the control accuracy.

11. For the 0-35-pound gas generator the desired propellant O/F ratio of 0.5 was obtained at the low pintle openings, while at the higher openings O/F ratio shifting occurred.

12. The low combustion gas temperatures using 20% water mixed by weight with UDMH, to further reduce the fuel rich O/F ratio temperatures, was achieved for the 0-35-pound gas generator tests.

13. The two methods of feedback signal control systems for the 0-35-pound gas generator proved that they could control the gas generation rate at the desired settings, maintain a constant combustion pressure, and provide hypergolic ignition and smooth combustion throughout the entire 30-second firings.

14. The estimated response time for the pintle from full closed to full open is 50 to 60 ms and frequency response from 10 to 20 cycles per second for the 0-35-pound gas generator.

15. The 0-35-pound gas generator with its electro-hydraulic servo control system can be used as a 0-35-pound variable thrust motor after the pintle and annular orifice seats have been redesigned.

RECOMMENDATIONS

1. Storable bipropellant combinations listed in this report that look promising should be further investigated by running experimental propellant evaluation tests for possible gas generator propellants. The studies should be concentrated on obtaining combustion temperatures of 1000°F or less, and determining heat-transfer rates to the propellants and tank walls.

2. The heat losses to the bulk of the liquid propellant appeared to be significant and should be considered in future analysis because of propellant surface reaction. The pressurization system using direct propellant pressurization is sensitive to variations in RFNA surface level such as the propellant forming a swirling motion during expulsion. If direct pressurization of propellants is used from the expulsion tank in the future, this should be further investigated, and possibly placing baffles on the inside of the tank would eliminate some of the swirling motion of the propellant.

3. Before designing a variable-demand liquid-propellant gas generator, the following experimental analysis should be performed: (a) eliminate O/F ratio shifting; (b) improve mixing performance; (c) obtain positive simultaneous propellant shut off; (d) obtain faster acting and high-accuracy control systems; (e) obtain an accurate means of

determining 0 - 0.400 gpm flow rates; (f) obtain a better means of accurately measuring temperatures; and (g) initiate a program to develop a combustion chamber for long-duration firings.

4. In future designs of the 0-35-pound gas generator injectors, both constant acting balanced forces on the pintle and equal hydraulic-system acting cavity volumes should be provided; this, in turn, will provide a mechanical gain balance in the opening and closing directions.

5. The Packrat II gas generator injector should be redesigned to eliminate the gold-brazed stainless-steel diaphragm used as part of the control system; this also would reduce the high cost and difficulty in fabrication.

6. Both Packrat II and 0-35-pound gas generator injectors should have closer tolerance guiding surfaces and annular pintle seats to obtain better concentricity of propellant stream injection.

7. The 0-35-pound gas generator injector, if used as a flight gas generator, should utilize the fuel as the hydraulic servo-actuation fluid during firing; thus the fuel manifold and hydraulic supply pressure would be identical.

8. The Condor hot gas controlled bipropellant injector valve should be incorporated in a future Condor missile development as part of a centromix injector-control system, and be tested intensively for use as part of a fast-response mechanical self-pressure-regulating liquid-propellant gas generator pressurization system.

Appendix A

THEORETICAL AND EXPERIMENTAL PROPELLANT STUDIES

THEORETICAL PROPELLANT CALCULATIONS

The various theoretical performance characteristics were computed at O/F ratios of from 4:1 to 20:1, and 0.05 to 1:1. The majority of the computer calculations were at 1:1 for comparison purposes, and were not computed for other O/F ratios unless their combustion chamber temperatures were below 2500°F. The combustion chamber to pressurization tank pressure ratio, and combustion chamber to ambient pressure ratios were computed at 1200:1000 psi; 1000:700 psi; 1000:14.7 psi; 700:500 psi; 700:14.7 psi; 600:14.7 psi; 500:14.7 psi; 400:14.7 psi; and 300:14.7 psi.

The 1:1 O/F ratios for propellants that were computed are shown in Table 2. The most promising propellant combinations shown in Table 2 are RFNA with the following fuels: 50% C_8H_{18}-50% UDMH; 50% C_8H_{18}-50% N_2H_4; C_2H_5OH; MHF-3; UDMH; 80% UDMH-20% H_2O; NH_3; 95% NH_3-5% LiOH; 90% NH_3-10% H_2O; and 80% NH_3-20% H_2O. The other propellant combinations with the lowest temperatures are WFNA with CH_3OH, and NH_3. All of these promising propellant combinations were compared with a chamber pressure of 700/500 psi. They had c^*, chamber, and chamber exit temperature ranges of 3785 to 4643 ft/sec, 1729 to 1983°F, and 1590 to 1831°F, respectively.

Some theoretical propellant calculations of promising propellant mixtures are shown in Table 3. Even though some of the oxidizer rich propellant combinations may have lower temperatures than the fuel rich propellant combinations, the combustion efficiency may not be as good as the fuel rich mixture ratios. The mixture ratios shown in Table 3 are for comparison purposes only and are not intended to be used at these mixture ratios without running some experimental tests to substantiate their combustion stability.

The more promising theoretical propellant combinations that had low combustion temperatures at an O/F oxidizer and fuel rich ratio range of 0.05 to 20 are compared and shown in Fig. 13-16.

TABLE 2. Theoretical Propellant Calculations at O/F Mixture Ratios of 1:1

Propellant combination	c*, ft/sec	Chamber temperature, °F	Exit temperature, °F	P_c/P_e, psi
RFNA/NH_3	4,273	1983	1806	700/500
RFNA/95% NH_3-5% LiOH	3,944	1748	1590	700/500
RFNA/NH_3	4,281	1983	520	700/14.7
RFNA/95% NH_3-5% LiOH	3,962	1748	449	700/14.7
RFNA/90% NH_3-10% H_2O	4,264	2092	1912	700/500
RFNA/90% NH_3-10% H_2O	4,283	2092	572	700/14.7
RFNA/80% NH_3-20% H_2O	4,285	2202	2020	700/500
RFNA/80% NH_3-20% H_2O	4,281	2202	640	700/14.7
WFNA/NH_3	4,233	1919	1745	700/500
WFNA/NH_3	4,237	1919	498	700/14.7
WFNA/CH_3OH	4,159	2292	2118	700/500
WFNA/CH_3OH	4,266	2291	1090	700/14.7
RFNA/50% CH_3OH-50% UDMH	5,282	3924	3663	700/500
RFNA/50% CH_3OH-50% UDMH	5,295	3924	1629	700/14.7
RFNA/C_2H_5OH	3,785	1729	1646	700/500
RFNA/C_2H_5OH	4,037	1729	1073	700/14.7
RFNA/50% C_8H_{18}-50% UDMH	4,548	2260	2092	700/500

TABLE 2. (Contd)

Propellant combination	c^*, ft/sec	Chamber temperature, °F	Exit temperature, °F	P_c/P_e, psi
RFNA/50% C_8H_{18}-50% UDMH	4,776	2261	1246	700/14.7
RFNA/50% C_8H_{18}-50% N_2H_4	4,220	1945	1831	700/500
RFNA/50% C_8H_{18}-50% N_2H_4	4,480	1946	1128	700/14.7
RFNA/UDMH	4,511	2293	2105	700/500
RFNA/UDMH	4,666	2290	1190	600/14.7
RFNA/UDMH	4,588	2277	1237	300/14.7
RFNA/80% UDMH-20% H_2O	4,551	2488	1143	600/14.7
RFNA/80% UDMH-20% H_2O	4,508	2488	1218	300/14.7
RFNA/MHF-3[a]	4,666	2376	2266	1200/1000
RFNA/MHF-3[a]	4,643	2362	2158	700/500
RFNA/MMH	4,962	3049	2914	1200/1000
RFNA/MMH	4,962	3048	2802	700/500
RFNA/50% N_2H_4-50% H_2O	4,365	3042	2931	1200/1000
RFNA/50% N_2H_4-50% H_2O	4,395	3039	2837	700/500
RFNA/70% N_2H_4-30% H_2O	5,141	4084	3951	1200/1000
RFNA/70% N_2H_4-30% H_2O	5,117	4074	3835	700/500
WFNA/MMH	4,911	2975	2842	1200/1000

TABLE 2. (Contd)

Propellant combination	c*, ft/sec	Chamber temperature, °F	Exit temperature, °F	P_c/P_e, psi
WFNA/MMH	4,920	2975	2733	700/500
RFNA-(20% NO_2)/UDMH	4,631	2456	2344	1200/1000
RFNA-(20% NO_2)/UDMH	4,602	2452	2236	1000/700
RFNA-(20% NO_2)/UDMH	4,608	2442	2233	700/500
RFNA(20% NO_2)/UDMH	4,804	2450	1173	1000/14.7
RFNA(20% NO_2/ 80% UDMH- 20% H_2O	4,263	1847	984	1000/14.7
RFNA(20% NO_2)/ 50% UDMH- 50% NH_3	4,670	2302	1023	1000/14.7

NOTE: Except where noted, all RFNA computations were with RFNA(14% NO_2, 1.5% H_2O)

[a]O/F ratio of 0.8:1.

TABLE 3. Some Theoretical Propellant Calculations of Promising Propellant Mixtures

Propellant combination	O/F	c*, ft/sec	Chamber temperature, °F	Exit temperature, °F	P_c/P_e psi
RFNA(14)/UDMH	0.4:1	4,141	1816	1722	700/500
RFNA(14)/UDMH	0.4:1	4,425	1795	1061	600/14.7
RFNA(14)/UDMH	0.4:1	4,399	1770	1075	500/14.7
RFNA(14)/UDMH	0.4:1	4,369	1741	1092	400/14.7
RFNA(14)/UDMH	0.4:1	4,328	1704	1113	300/14.7
RFNA(14)/UDMH	20:1	2,464	1045	260	300/14.7
RFNA(14)/UDMH	10:1	3,630	2600	1195	300/14.7
RFNA(14)/80% UDMH-20% H_2O	0.4:1	4,098	1595	965	600/14.7
RFNA(14)/80% UDMH-20% H_2O	0.4:1	4,074	1573	979	500/14.7
RFNA(14)/80% UDMH-20% H_2O	0.4:1	4,051	1546	995	400/14.7
RFNA(14)/80% UDMH-20% H_2O	0.4:1	4,012	1512	1017	300/14.7
RFNA(14)/45% UDMH-45% C_8H_{18}-10% H_2O	0.4:1	4,470	1799	1126	700/14.7
RFNA(14)/50% UDMH-50% C_8H_{18}	0.4:1	4,292	1913	1820	700/500
RFNA(14)/50% UDMH-50% C_8H_{18}	0.4:1	4,644	1913	1173	700/14.7
RFNA(14)/50% UDMH-50% CH_3OH	0.4:1	4,564	2173	2011	700/500
RFNA(14)/50% UDMH-50% CH_3OH	0.4:1	4,791	2173	1173	700/14.7
RFNA(14)/CH_3OH	0.4:1	3,523	1469	1406	700/500

TABLE 3. (Contd)

Propellant combination	O/F	c*, ft/sec	Chamber temperature °F	Exit temperature, °F	P_c/P_e psi
RFNA(14)/CH_3OH	0.4:1	3,727	1469	878	700/14.7
RFNA(14)/50% C_8H_{18}-50% N_2H_4	0.4:1	3,904	1646	1567	700/500
RFNA(14)/50% C_8H_{18}-50% N_2H_4	0.4:1	4,169	1646	950	700/14.7
RFNA(14)/MMH	0.4:1	4,414	1949	1889	1200/1000
RFNA(14)/MMH	0.4:1	4,345	1768	1872	700/500
RFNA(14)/MMH	10:1	3,299	2066	1972	1200/1000
RFNA(14)/MMH	10:1	3,271	2060	1897	700/500
RFNA(14)/MMH	14:1	2,664	1314	1244	1200/1000
RFNA(14)/MMH	14:1	2,693	1314	1185	700/500
RFNA(14)/MHF-3	0.4:1	4,447	1966	1904	1200/1000
RFNA(14)/MHF-3	0.4:1	4,400	1888	1781	700/500
RFNA(14)/MHF-3	10:1	3,222	1930	1841	1200/1000
RFNA(14)/MHF-3	10:1	3,198	1932	1768	700/500
RFNA(14)/MHF-3	14:1	2,599	1210	1142	1200/1000
RFNA(14)/MHF-3	14:1	2,644	1207	1084	700/500
RFNA(14)/NH_3	0.4:1	2,785	561	516	700/500
RFNA(14)/NH_3	0.4:1	2,983	561	187	700/14.7
RFNA(14)/90% NH_3-10% H_2O	0.4:1	2,763	557	512	700/500
RFNA(14)/90% NH_3-10% H_2O	0.4:1	2,944	557	174	700/14.7
RFNA(14)/80% NH_3-10% H_2O	0.4:1	2,717	555	509	700/500

TABLE 3. (Contd)

Propellant combination	O/F	c*, ft/sec	Chamber temperature, °F	Exit temperature, °F	P_c/P_e psi
RFNA(14)/80% NH_3 20% H_2O	0.4:1	2,896	555	170	700/14.7
RFNA(14)/NH_3	0.8:1	3,832	1391	1249	700/500
RFNA(14)/NH_3	0.8:1	3,886	1390	379	700/14.7
RFNA(14)/90% NH_3- 10% H_2O	0.8:1	3,866	1489	1342	700/500
RFNA(14)/90% NH_3- 10% H_2O	0.8:1	3,890	1488	390	700/14.7
RFNA(14)/80% NH_3- 20% H_2O	0.8:1	3,876	1595	1444	700/500
RFNA(14)/80% NH_3- 20% H_2O	0.8:1	3,897	1594	406	700/14.7
WFNA/MMH	10:1	3,319	2066	1973	1200/1000
WFNA/MMH	10:1	3,310	2066	1897	700/500
WFNA/MMH	12:1	2,999	1645	1566	1200/1000
WFNA/MMH	12:1	2,971	1648	1502	700/500
RFNA(20)/UDMH	0.5:1	4,576	1941	1070	1000/14.7
RFNA(20)/UDMH	0.4:1	4,212	1921	1864	1200/1000
RFNA(20)/UDMH	0.4:1	4,216	1894	1788	1000/700
RFNA(20)/UDMH	0.4:1	4,524	1894	1034	1000/14.7
RFNA(20)/UDMH	0.4:1	4,172	1844	1746	700/500
RFNA(20)/80% UDMH- 20% H_2O	0.5:1	4,041	1600	874	1000/14.7
RFNA(20)/80% UDMH- 20% H_2O	0.4:1	---	1427	773	1000/14.7
RFNA(20)/UDMH	10:1	3,669	2750	1273	300/14.7

NOTE: 1. RFNA(14) is RFNA(14% NO_2, 1.5% H_2O).
2. RFNA(20) is RFNA(20% NO_2).

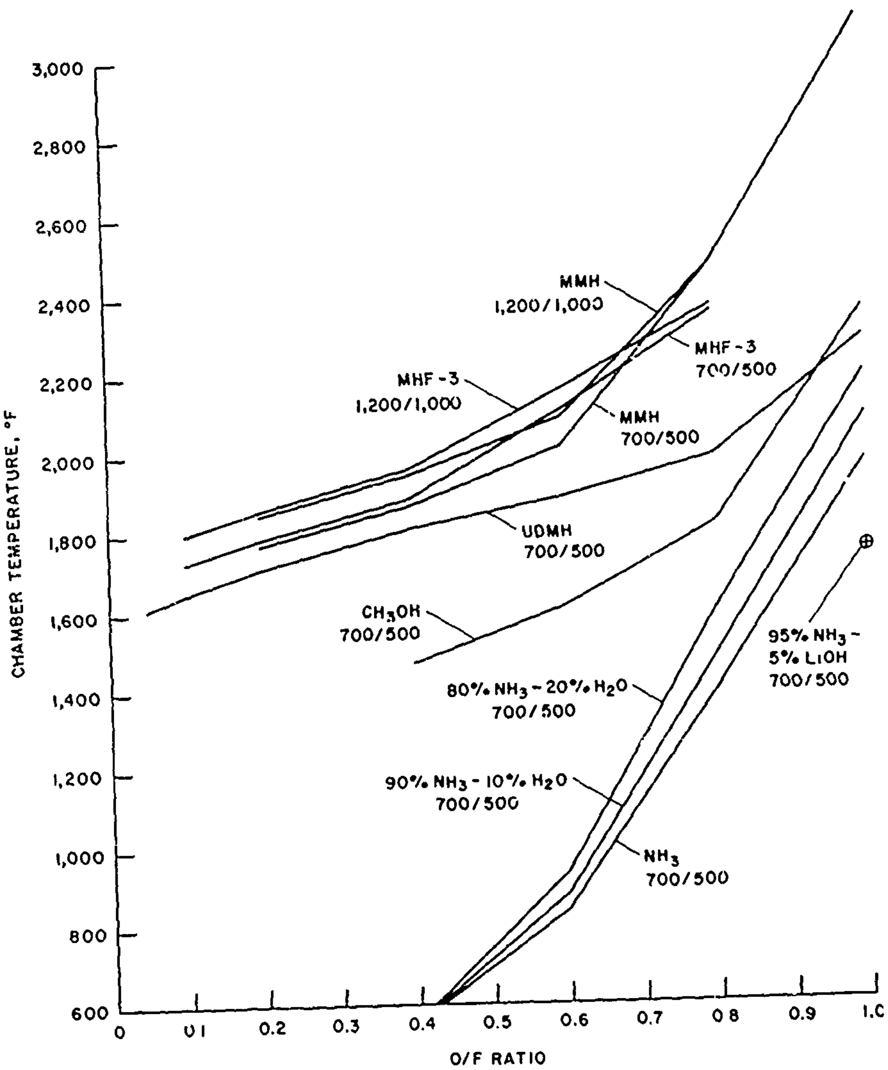


FIG. 13. Theoretical Calculations of RFNA (14% NO_2) With Selected Fuels at Various Combustion Chamber to Tank Pressures

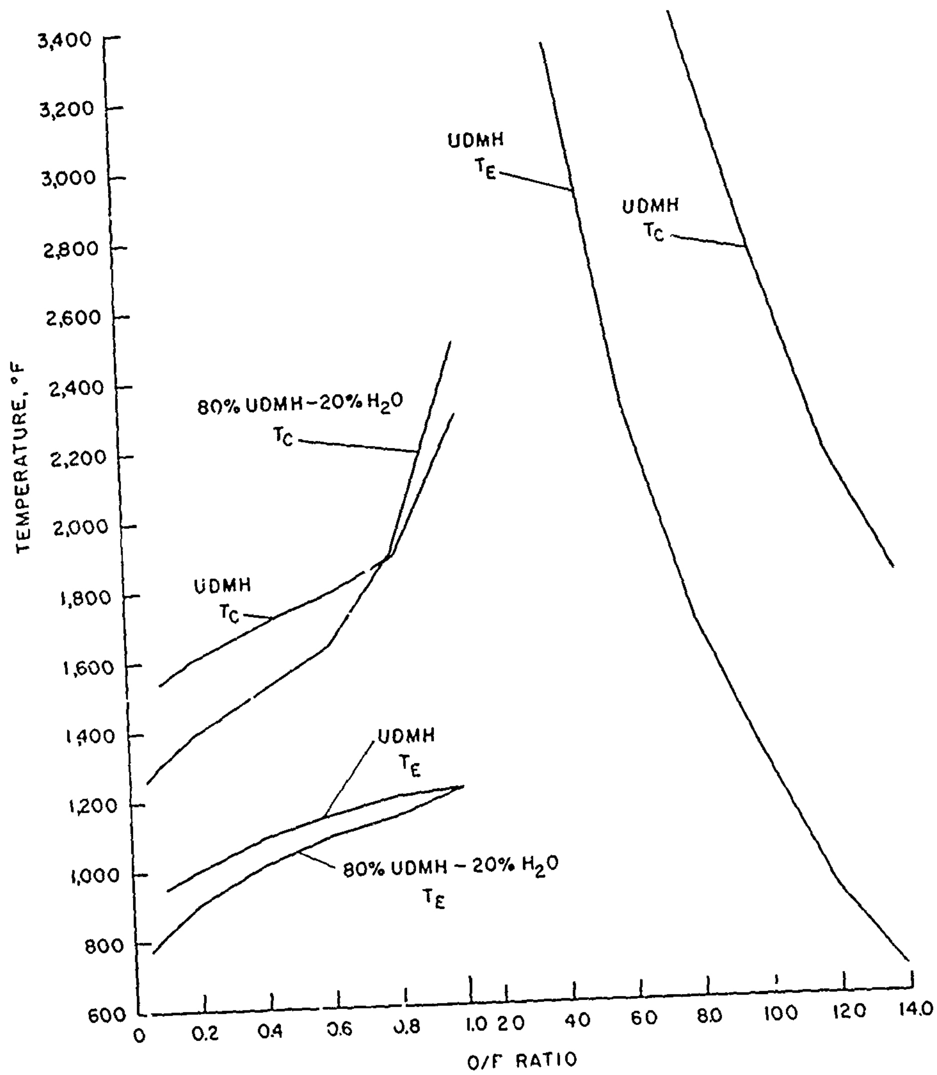


FIG. 14. Theoretical Calculations of RFNA (14% NO_2) Rich Versus UDMH Rich Mixture Ratios at 300 psia Combustion Chamber Pressure.

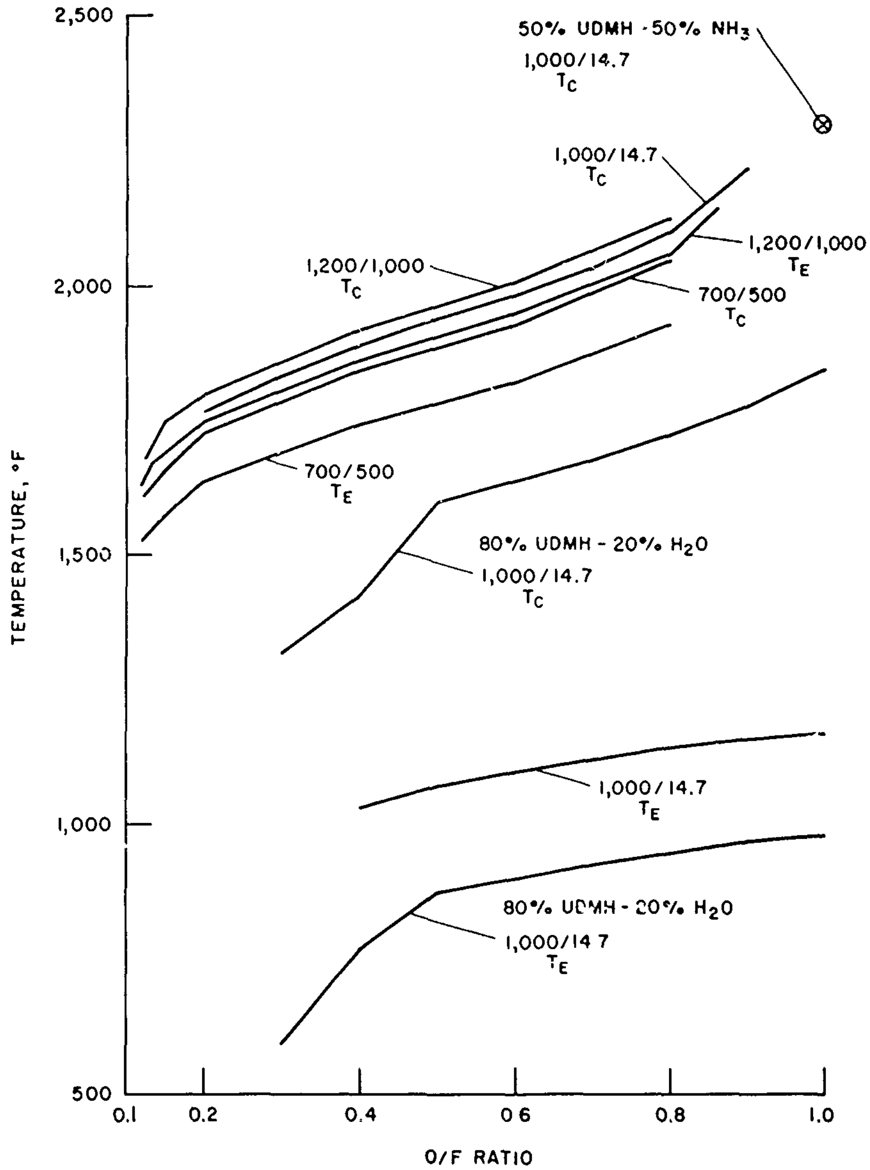


FIG. 15. Theoretical Calculations of RFNA (20% NO_2)/ UDMH, and 80% UDMH-20% H_2O at Various Combustion Chamber Pressures.

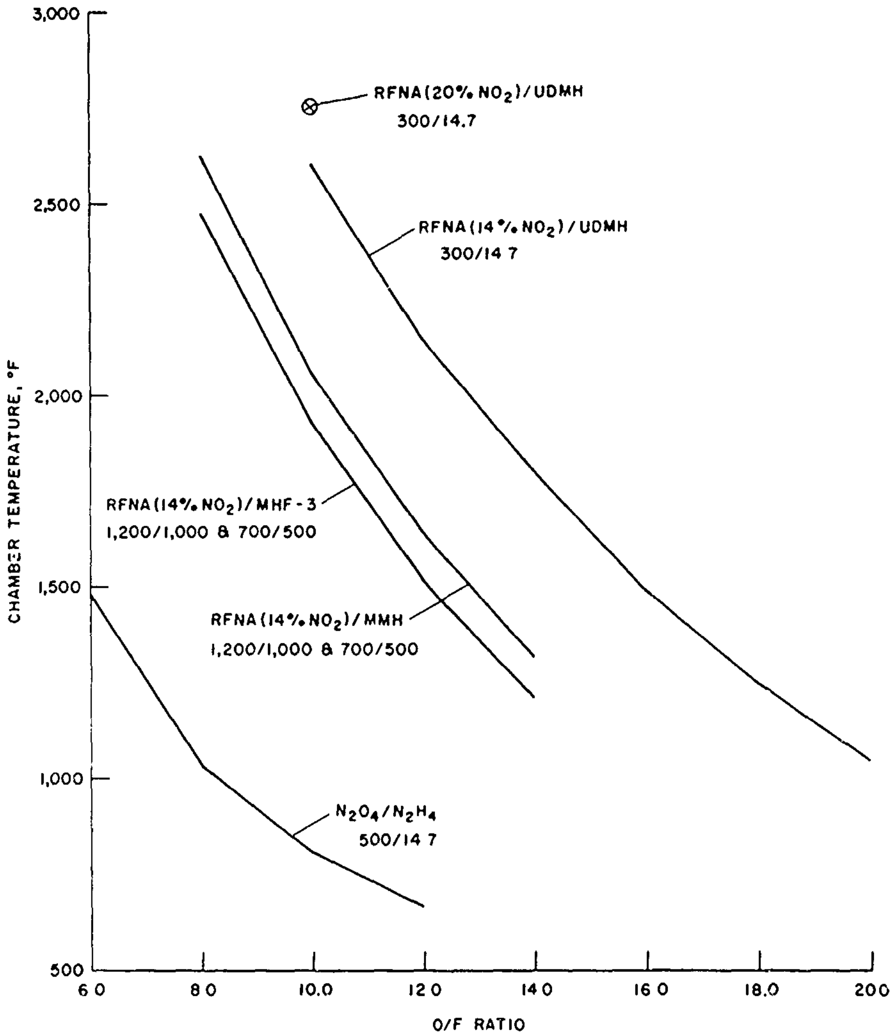


FIG. 16. Theoretical Calculations of Oxidizer Rich Mixture Ratios With Selected Fuels at Various Combustion Chamber Pressures.

Propellant chemical symbols are defined as follows:

Ammonia (liquid)	NH_3
Ethyl alcohol	C_2H_5OH
Hydrazine	N_2H_4
Methyl alcohol	CH_3OH
Mixed hydrazine fuel	MHF-3
Monomethylhydrazine	MMH (CH_3NH-NH_2)
Nitrogen dioxide	NO_2
Nitrogen tetroxide	N_2O_4
Inhibited red fuming nitric acid	IRFNA
N-Octane	(C_8H_{18})
Water	H_2O
White fuming nitric acid	WFNA

In Fig. 13 a theoretical performance comparison is made using RFNA (14% NO_2) with selected fuels at various combustion chamber to tank pressures. The most promising fuels were NH_3 and 95% NH_3-5% LiOH. The 5% LiOH was added to NH_3 to make it hypergolic with RFNA.

Figure 14 shows the theoretical performance comparison of RFNA (14% NO_2) oxidizer rich versus UDMH fuel rich mixture ratios at 300 psia combustion chamber pressure. The comparisons are made of both combustion chamber and exhaust gas temperatures, with 80% UDMH-20% H_2O being cooler than straight UDMH in the lower mixture ratios. In comparing the combustion chamber and exhaust gas temperatures of UDMH rich versus RFNA (14% NO_2) rich, the RFNA (14% NO_2) exhaust gas temperature is lower: and if the O/F ratio of RFNA (14% NO_2) is increased to 20 the combustion chamber temperature is also lower. Although the oxidizer rich mixture ratio may obtain lower temperatures than the fuel rich mixture ratios, the combustion efficiency is not as good as the fuel rich ratio. This is confirmed by the work done by Purdue University on the performance of RFNA and UDMH in gas generators (Ref. 1).

In Fig. 15 a theoretical performance comparison is made using RFNA (20% NO_2) as the oxidizer with straight UDMH and 80% UDMH-20% H_2O as the fuels at different O/F ratios and various combustion chamber pressures. The theoretical performance shows that by using 80% UDMH-20% H_2O the average c^*, combustion chamber, and exhaust gas temperatures are decreased. For the O/F range of 0.4 to 0.9 and a combustion chamber pressure of 1,000 psia, the average c^*, combustion chamber, and exhaust gas temperatures are decreased by 527 ft/sec, 373°F, and 200°F, respectively. Using RFNA (14% NO_2) instead of RFNA (20% NO_2), the temperatures are lowered on the average between 50 and 150°F.

Figure 16 shows a theoretical performance comparison of oxidizer rich mixture ratios with selected fuels at various combustion chamber

pressures. Although the N_2O_4/N_2H_4 and RFNA (14% NO_2)/MHF-3 propellant combinations showed the lowest combustion chamber temperatures, theoretical calculations were only made with RFNA (14% NO_2)/MHF-3. The theoretical calculations for N_2O_4/N_2H_4 were used from a Jet Propulsion Laboratory technical report and were used only for a comparison (Ref. 2).

EXPERIMENTAL PROPELLANT STUDIES

The experimental propellant studies were made with the Micromix test setup in Fig. 17-18. It is a test apparatus used extensively for evaluating and studying the ignition and combustion of liquid propellants. It was used to study the ignition and combustion of RFNA and UDMH at low O/F ratios.

The results of the tests made at the low O/F mixture ratios are shown in Table 4. The four methods used in obtaining the temperatures are shown in Fig. 19A, B, C, and D. The first twelve tests were made with the small chamber setup (Fig. 19A). The chamber was made of stainless steel and had the following design characteristics: L^* 70 inches, nozzle diameter 0.147 inch, a Y mix injector with orifice diameter of 0.070 inch, mixing length 0.250 inch, and a P_a of 13.5 psia.

The first six tests used IRFNA and UDMH and the next six tests used a propellant mixture of IRFNA and UDMH with 20% water by volume added to the UDMH. The addition of the 20% water to the UDMH lowered the temperature by 500°F. Although the propellant mixtures for these 12 tests were hypergolic, the combustion was either rough or unsteady. Most of the combustion for all of these tests took place outside of the chamber, but combustion would not be a problem with a 250- to 300-inch L^* chamber.

The last tests 27 through 32 with an IRFNA-UDMH O/F ratio as low as 0.247 were hypergolic and combustion was fairly smooth. This proved the importance of having a long L^* combustion chamber to allow for complete propellant mixing. The enclosed tube (Fig. 19D) was the best method for evaluating IRFNA-UDMH at the very low O/F ratios.

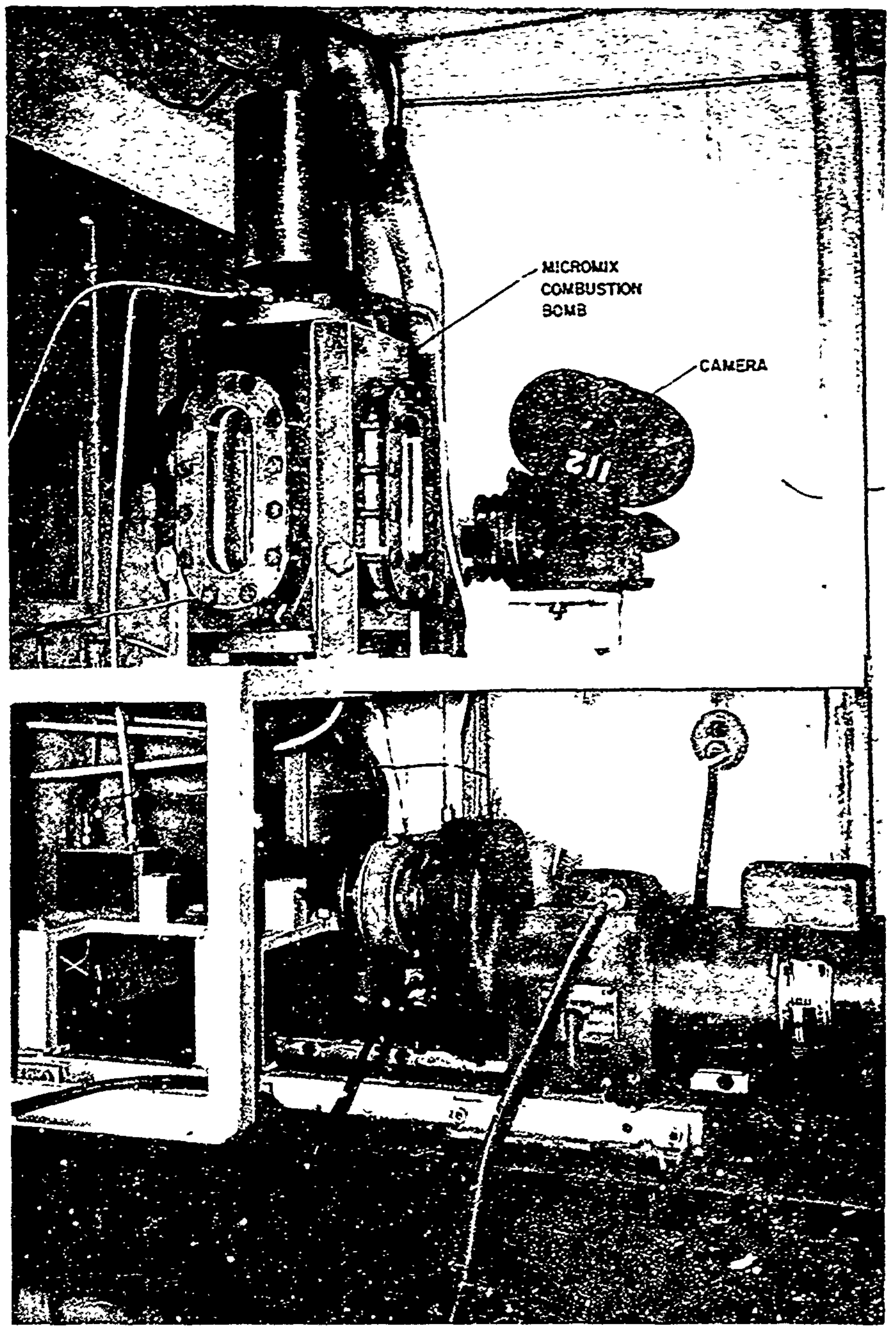


FIG. 17. Micromix Experimental Test Setup.

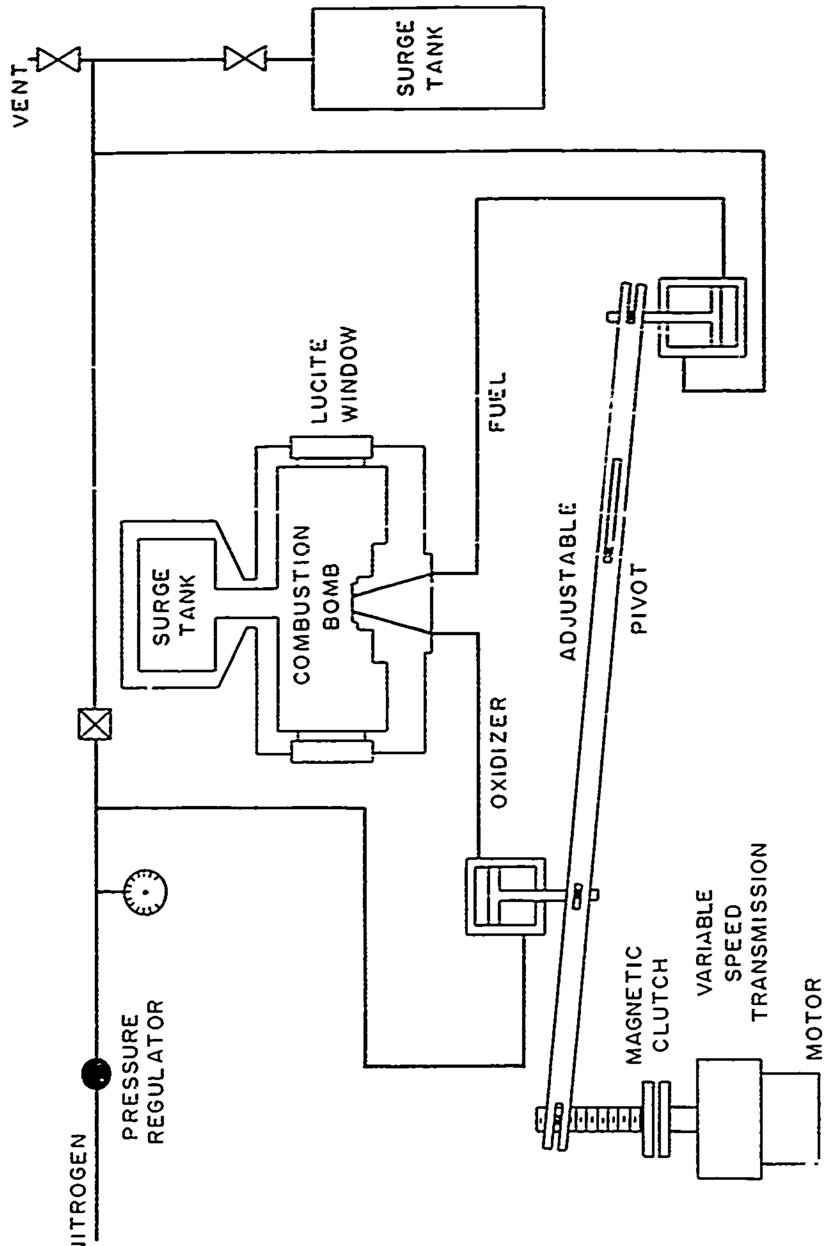


FIG. 18. Micromix Schematic Diagram.

TABLE 4. Micromix Experimental Propellant Studies

Test no.	Mixture ratio O/F	Ignition characteristic and temp. measure. method	Flame temp., °F	Chamber pressure, psia	Oxid. flow rate, gm/sec	Fuel flow rate, gm/sec	Oxid. line pressure,[a] no.	Comb. stability and propellant decomposition	Propellant used and % H_2O added
1	0.382	satisfactory ignition	1100-1300	20	0.284	1.482	3	somewhat rough	IRFNA-UDMH
2	0.382	small chamber (Fig. 19 A) for tests 1-12	1350	23	0.400	2.120	4		
3	0.382		1100	24	0.400	2.120	4		
4	0.382		1500	16.5	0.162	---	2		
5	0.382		700-900	29	0.511	2.652	5	rough	
6	0.382		1300	20	0.284	1.482	3	smooth	
7	0.478	borderline ignition in tests 7-10	155		0.162		2	rough-on & off	26.6% IRFNA by wt. 55.7% UDMH 17.7% H_2O of total propellant wt. added to UDMH (or 20% H_2O by volume added to the UDMH for tests 7-12)
8	0.478		167	16	0.284	1.186	3		
9	0.478		167	18	0.400	1.696	4		
10	0.478		190	25	0.511	2.122	5	steadier	
11	0.478	satisfactory ignition in tests 11-32	194	32	0.693	2.891	7	fairly steady	
12	0.478		200	33	0.995	4.138	10	rough	

TABLE 4 (Contd)

Test no.	Mixture ratio O/F	Ignition characteristic and temp. measure. method	Flame temp., °F	Chamber pressure, psia	Oxid. flow rate, gm/sec	Fuel flow rate, gm/sec	Oxid. line pressure,[a] no.	Comb. stability and propellant decomposition	Propellant used and % H_2O added
13	0.308	Open flame (Fig. 19 B) for tests 13-17	210	---	0.295	0.960	3	Intermittent combustion	IRFNA-(UDMH-20% H_2O by volume) or 18.9 wt. %IRFNA 61.5 wt. %UDMH 19.6 wt. %H_2O added to UDMH for tests 13-16
14	0.308		---	---	0.716	2.320	7		
15	0.308		---	---	0.716	2.320	7		
16	0.308		164	---	0.716	2.320	7		
17	0.246		154	---	0.716	2.928	7	Rougher than with water	IRFNA-UDMH for tests 17-32
18	0.246	Combustion bomb (Fig. 19 C)	1650	---	0.716	2.928	7		
19	0.246	Enclosed tube (Fig. 19 D)	715	---	0.716	2.928	7		
20[b]	0.246	Combustion bomb (Fig. 19 C) for tests 20-26	338	65	0.716	2.928	7	Fair combustion for tests 20-26 and excess UDMH after tests	
21	0.246		318	75	0.716	2.928	7		
22	0.246		347	40	0.535	2.168	5		
23	0.246		347	128	0.535	2.168	5		
24[c]	0.246		---	81	0.535	2.168	5		
25	0.246		430	70	0.535	2.168	5		
26	0.246		480	89	0.535	2.168	5		

TABLE 4. (Contd)

Test no.	Mixture ratio O/F	Ignition characteristic and temp. measure. method	Flame temp., °F	Chamber pressure, psia	Oxid. flow rate, gm/sec	Fuel flow rate, gm/sec	Oxid. line pressure,[a] no.	Comb. stability and propellant decomposition	Propellant used and % H_2O added
27	0.246	Fairly smooth ignition	554	---	0.535	2.168	5	Combustion fairly smooth for tests 27-32	
28	0.246	Enclosed tube (Fig. 19 D) for tests 27-32	715	---	0.716	2.928	7		
29	0.246		680	---	0.295	1.200	3		
30	0.436		720	---	0.600	2.610	5		
31	0.436		830	---	0.801	3.561	7		
32	0.436		830	---	0.321	1.470	3		

[a]Numbers in oxid. line pressure column are speed settings for flow rate.
[b]Tests 20-23, temperature is that of products in enclosed combustion bomb.
[c]Tests 24-26, temperature is that of gas products.

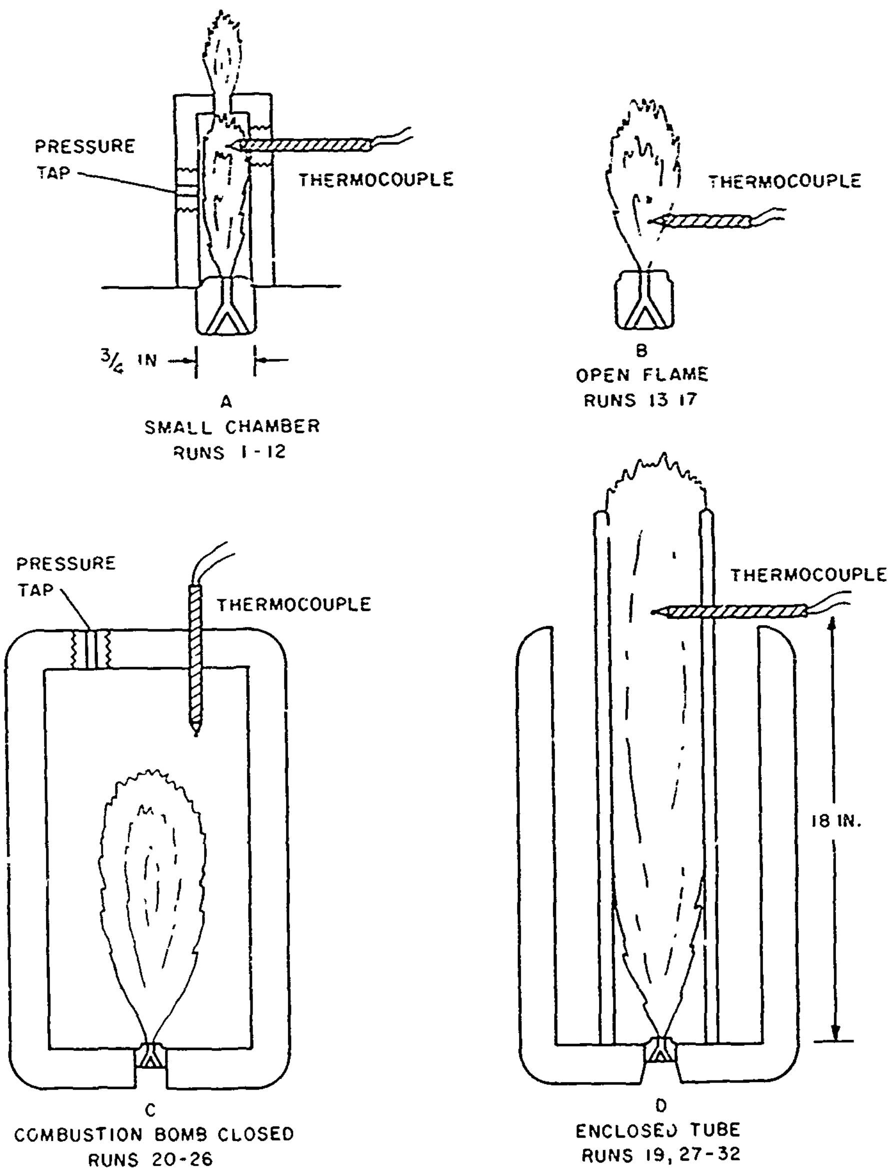


FIG. 19. Micromix Propellant Studies of Temperature Measurement Methods.

Appendix B

PACKRAT II VARIABLE DEMAND GAS GENERATOR PROGRAM

PROPELLANT SELECTION

Since the hot gases would come in direct contact with surfaces of either the IRFNA or the UDMH, it was desirable to use an oxidizer rich and a fuel rich gas generator. Also, since the propellant supply might come from the main booster motor propellant tank which used IRFNA and UDMH, it was desirable to use this propellant combination for the liquid-propellant gas-generator pressurization system.

PACKRAT II GAS-GENERATOR INJECTOR ASSEMBLY

This led to the research, and feasibility experimental development of an oxidizer rich hypergolic bipropellant liquid-propellant variable-area injector assembly (Fig. 20). The injector assembly had but one moving part which was the pintle, and was made up of several components as follows: a core piece, a housing, a deflector ring, and a pintle-retainer weldment. An exploded view of the injector hardware is shown in Fig. 21.

Core Piece

The core piece had a cavity running through the center of it for the fuel to flow through. It acts as an annular fuel-orifice seat for the metering pintle because of its central position. The annular orifice seat was designed to have an angle of 8 degrees ± 15 minutes. The core piece screws and seals into the pintle-retainer weldment extending through it, and can thereby be adjusted for different fuel O/F ratio settings.

Injector Housing

The front face of the housing provides the annular oxidizer orifice seat for the pintle. The annular oxidizer orifice seat was designed to have an angle of 20 degrees ± 15 minutes. The housing contains a fitting which forms a passageway for the oxidizer to flow through and thereby forming the outer housing for the injector.

Deflector Ring

The deflector ring in front of the injector housing was held in place by a retainer ring. The surface inside the deflector ring has an angle of 30 degrees ± 15 minutes plus two 0.060-inch steps to improve the propellant mixing.

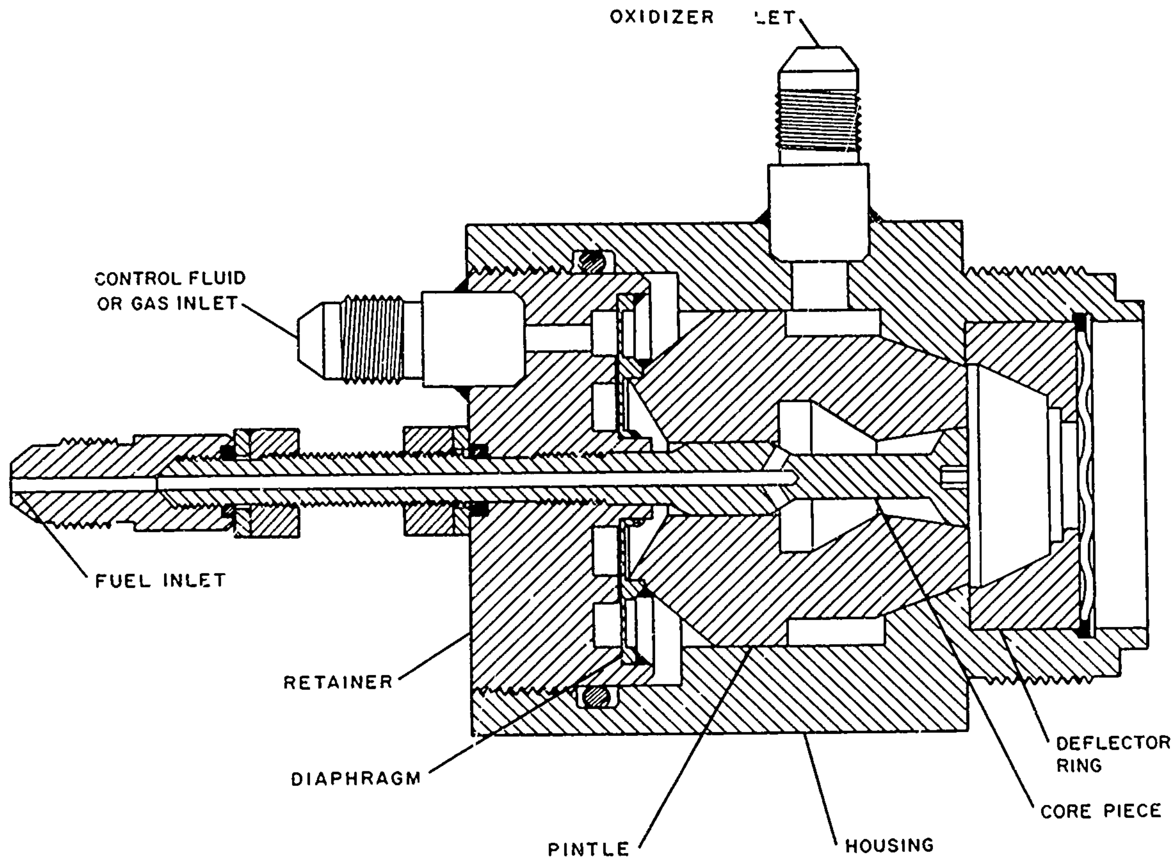


FIG. 20. Packrat II Gas Generator Variable-Area-Injector Assembly.

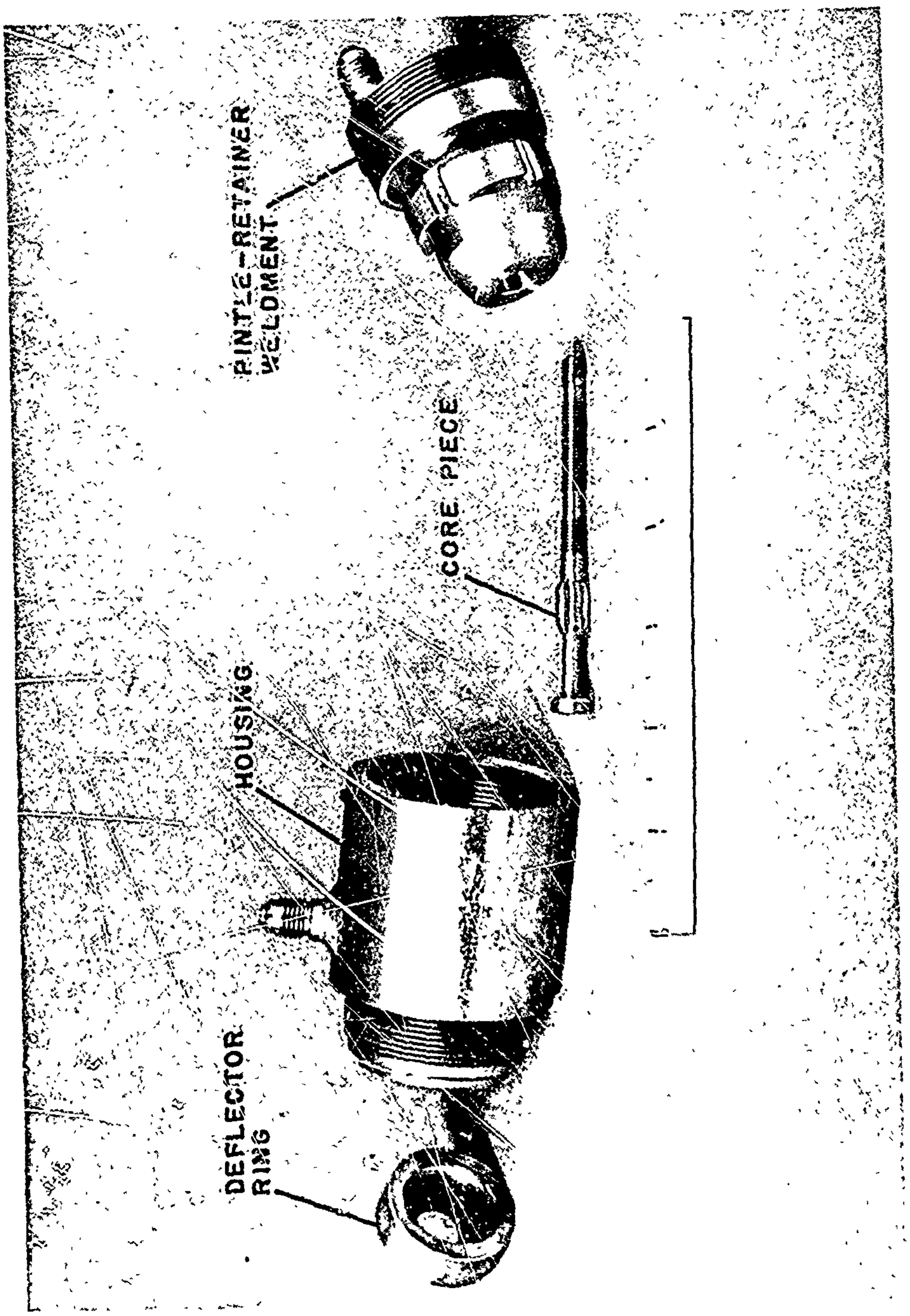


FIG. 21. Exploded View of Packrat II Gas Generator Variable-Area-Injector Hardware.

Pintle-Retainer Weldment

The pintle-retainer weldment was held together by a stainless steel diaphragm which was gold brazed to the pintle and pintle retainer. This forms a cavity on the aft side of the diaphragm whereby a force can be applied by the gases fed back from the combustion or main propellant tank. By having the pintle-retainer weldment screwed and sealed into the housing, the pintle can be adjusted for different oxidizer O/F ratio settings.

The annular diameters and angles of the front face of the pintle form the annular oxidizer and fuel orifice seats. The pintle is the only moving component of the injector.

CONTROL SYSTEM OPERATION

The injector, when assembled, has an oxidizer and fuel cavity on each side of the pintle. The fuel flows outward through the inner annulus of the pintle and the oxidizer flows inward through the outer annulus of the pintle to impinge upon each other, so that when the pintle is opened or closed both propellants are modulated simultaneously at a proportional O/F ratio throughout the pintle travel.

The gas-generator propellant-pressure forces acting on the pintle tend to force the pintle open, when there are no combustion-pressure forces acting on the pintle front surface. The forces acting on the pintle allow enough flow of propellants for combustion to start, so that the combustion gases are then fed back to the aft cavity of the diaphragm. The diaphragm can then be deflected up to a maximum of 0.0155 inch aft or forward to force the pintle to either open, close, or maintain an equilibrium position, depending on the combustion-pressure forces acting on the aft surface of the diaphragm (Fig. 22).

Therefore, the increasing or decreasing of the combustion pressures gives a control system that is directly self-pressure regulating by the generated hot gases and without any electronics. Figure 23 shows this gas generator in a possible pressurization configuration.

STATIC TESTS

The following four series of tests were performed:

1. Following the successfully completed water tests on the injector for design performance characteristics, the variable-area injector was successfully fired seven times for the first series using the propellant combination of RFNA/UDMH.

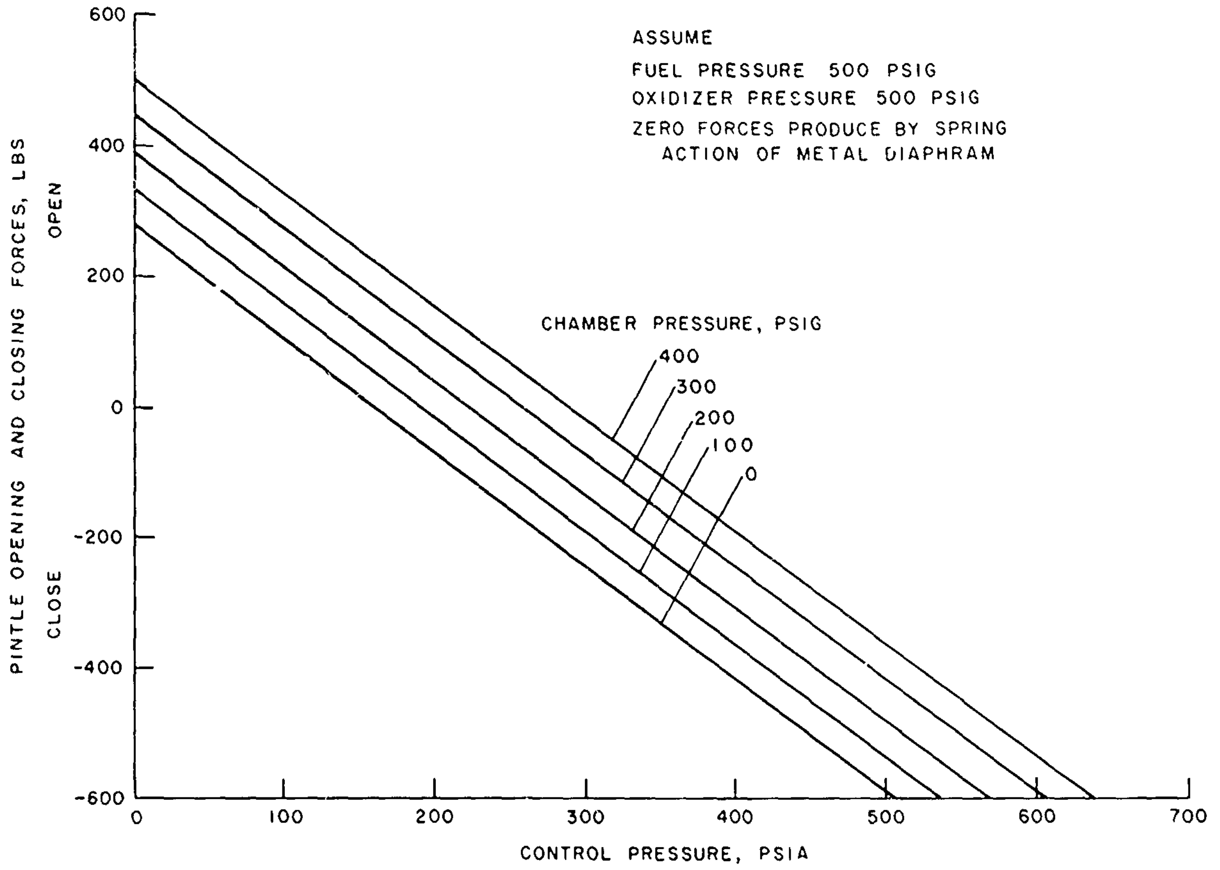


FIG. 22. Theoretical Pintle Opening and Closing Forces Versus Control Pressures.

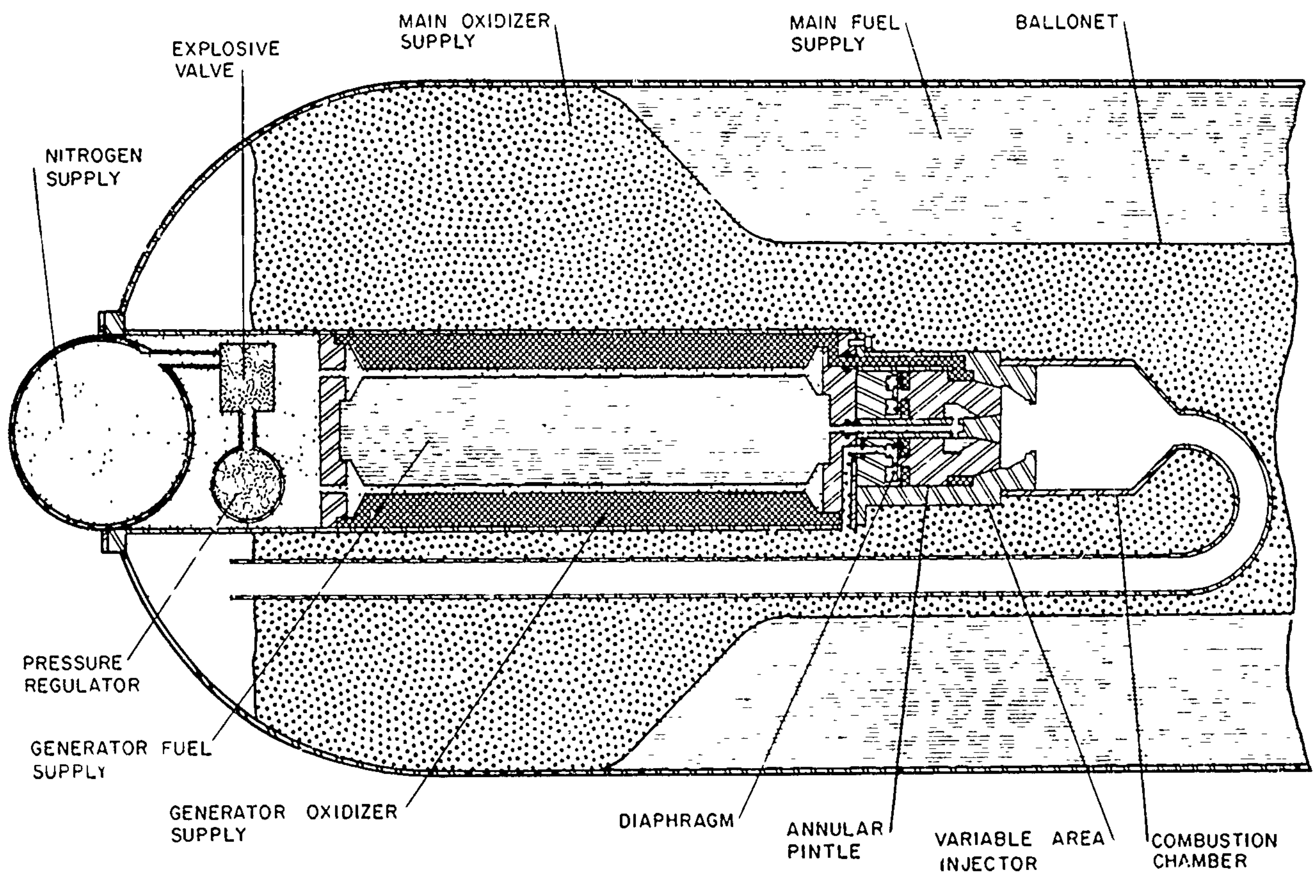


FIG. 23. A Packrat II Gas Generator Pressurization Configuration.

Since no combustion chamber had been designed to be used with this injector, the injector was fired with a test chamber. The test chamber was 4.5 inches in diameter, 24 inches in length, with a 0.250-inch wall thickness, and a sonic exit nozzle of 0.4 inch in diameter that could be removed and replaced. Although the test chamber (Fig. 24-25) had an L^* of 1,182 inches, it was not intended to be used as the combustion chamber. It was intended to be used as an accumulator for the generated gases in testing out the self-pressure regulating control system of the gas generator. The firings were made with O/F ratios of 6:1 to 1:1, and the gas generating total flow rates were varied between 0 and 0.435 lb/sec by manually regulating the nitrogen pressure on the pintle control. The pintle control was designed to be regulated by the pressure of the generated gases; however, for simplification in testing out the gas generator in the first hot firing series, nitrogen was used to independently control the pintle.

The chamber pressure was varied from 440 to 0 to 440 psig by the nitrogen control pressure. The combustion was smooth throughout each run and the chamber pressures remained constant at each control-pressure setting. The hysteresis effect on the control system, which was experienced on the water tests, was also experienced on all the hot firings. Figure 26 shows the control pressure versus chamber pressure effect for one of the runs.

2. The second static-test series was run with the chamber pressure controlling the pintle. Using IRFNA-UDMH as the propellant combination and the self-pressure regulating control feature of the gas generator, the results showed that the gas generator control system regulated the chamber pressure from 385 psig to 365 psig when a 25% increase in gas flow rate was demanded. The tests were considered a complete success, and all of the hardware upon examination looked very good. In order to improve the gas generator response time, and improve the accuracy of positioning the pintle, the pintle and core piece were modified (1) to eliminate friction between their two surfaces, (2) to try to obtain complete shut-off of the fuel annulus, and (3) to increase the volume of the fuel cavity.

3. A third series of five static tests, using IRFNA-UDMH as the propellants and the self-pressure regulation control system, was made in order to evaluate the modifications on the pintle and core piece. When compared to previous tests, the tests showed a significant response gain at all pressure ranges. The self-pressure regulating control of the gas generator maintained test chamber pressures between 400 and 440 psig when a change of 15 to 35% increase in flow rate was demanded. For gas generator propellant tank pressures of 525 psig, the control system regulated the chamber pressure between 440 and 420 psig, and the O/F ratio varied between 9.5:1 and 10.7:1.

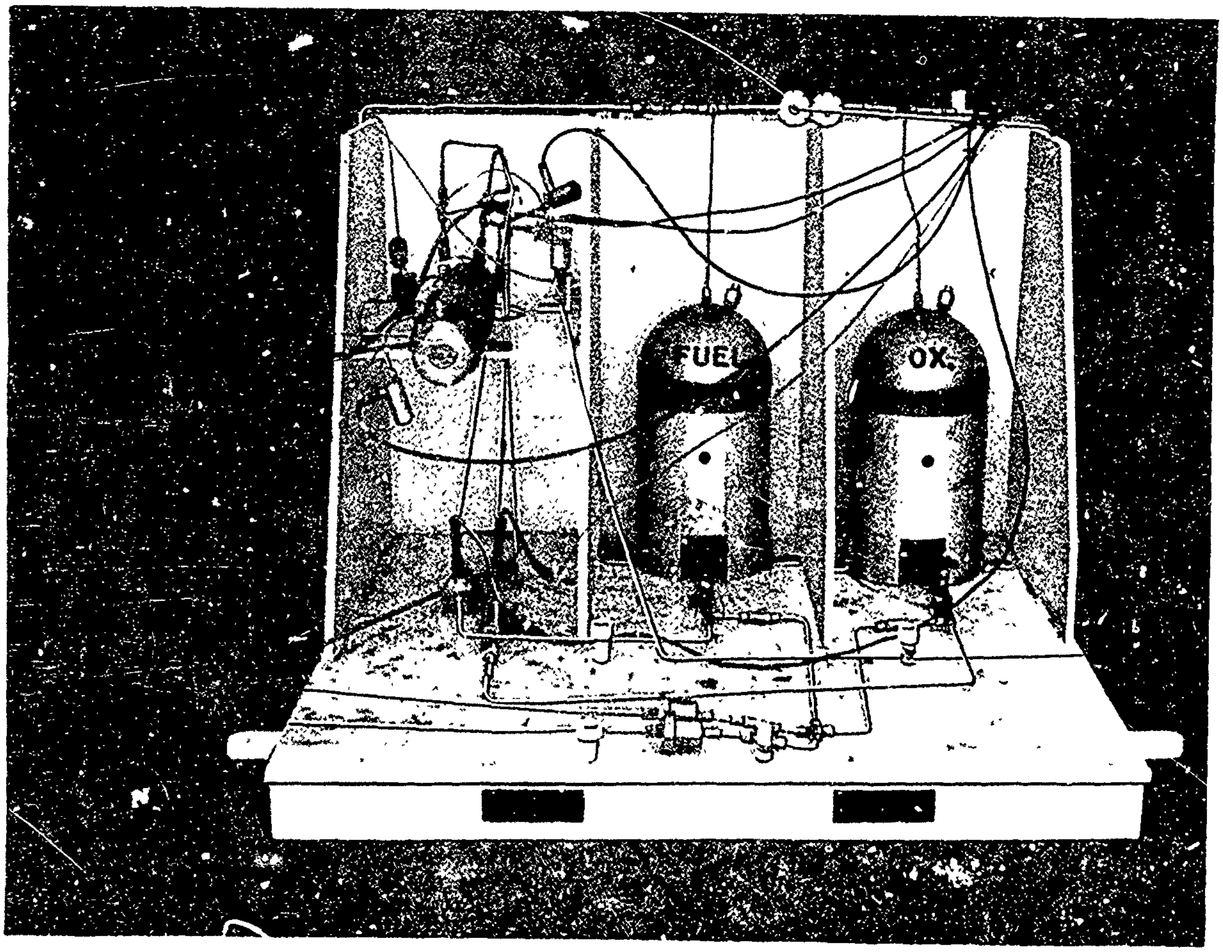


FIG. 24. Packrat II Gas Generator and Static Test Stand Setup.

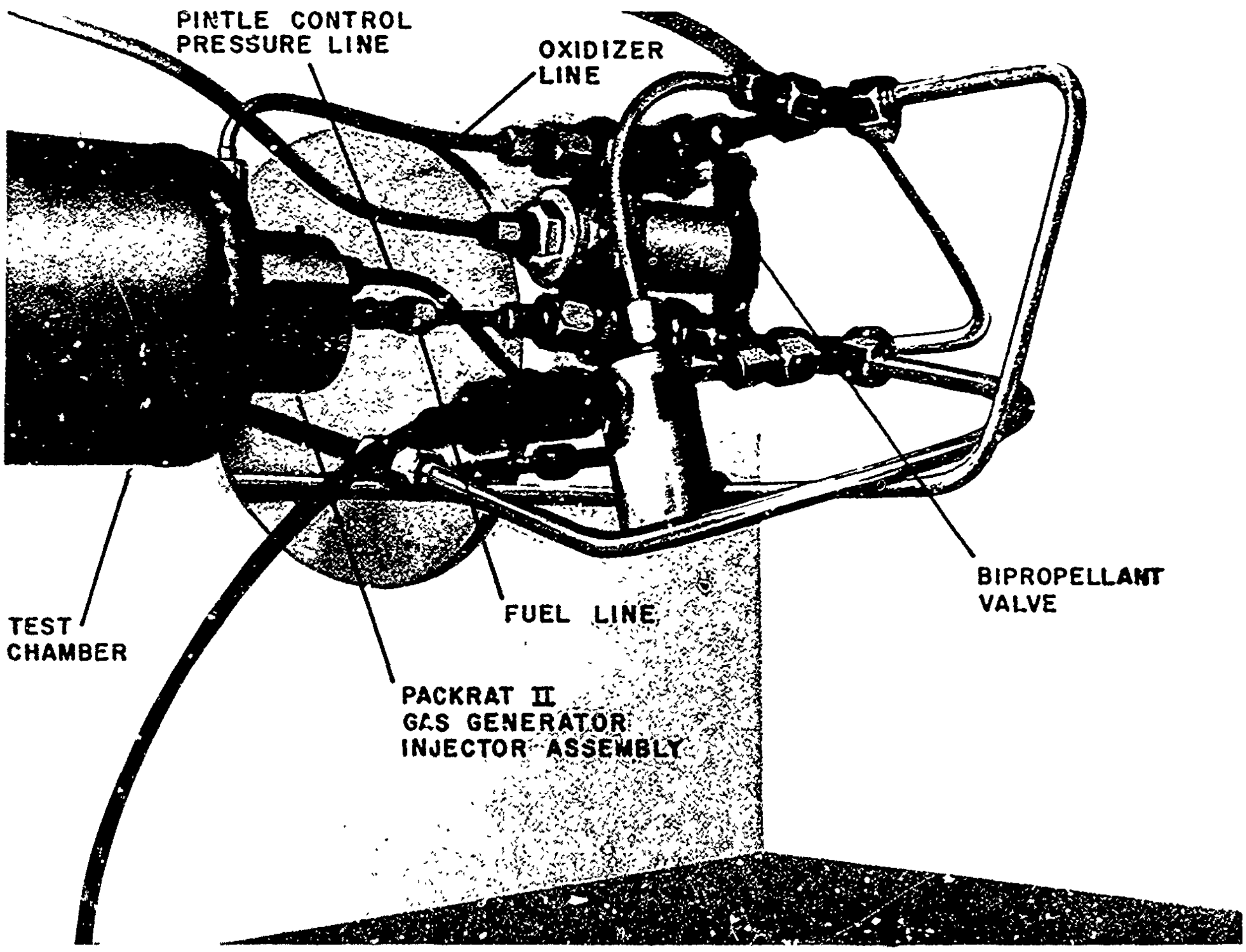


FIG. 25. After View of Test Chamber With Packrat II Gas Generator Control System

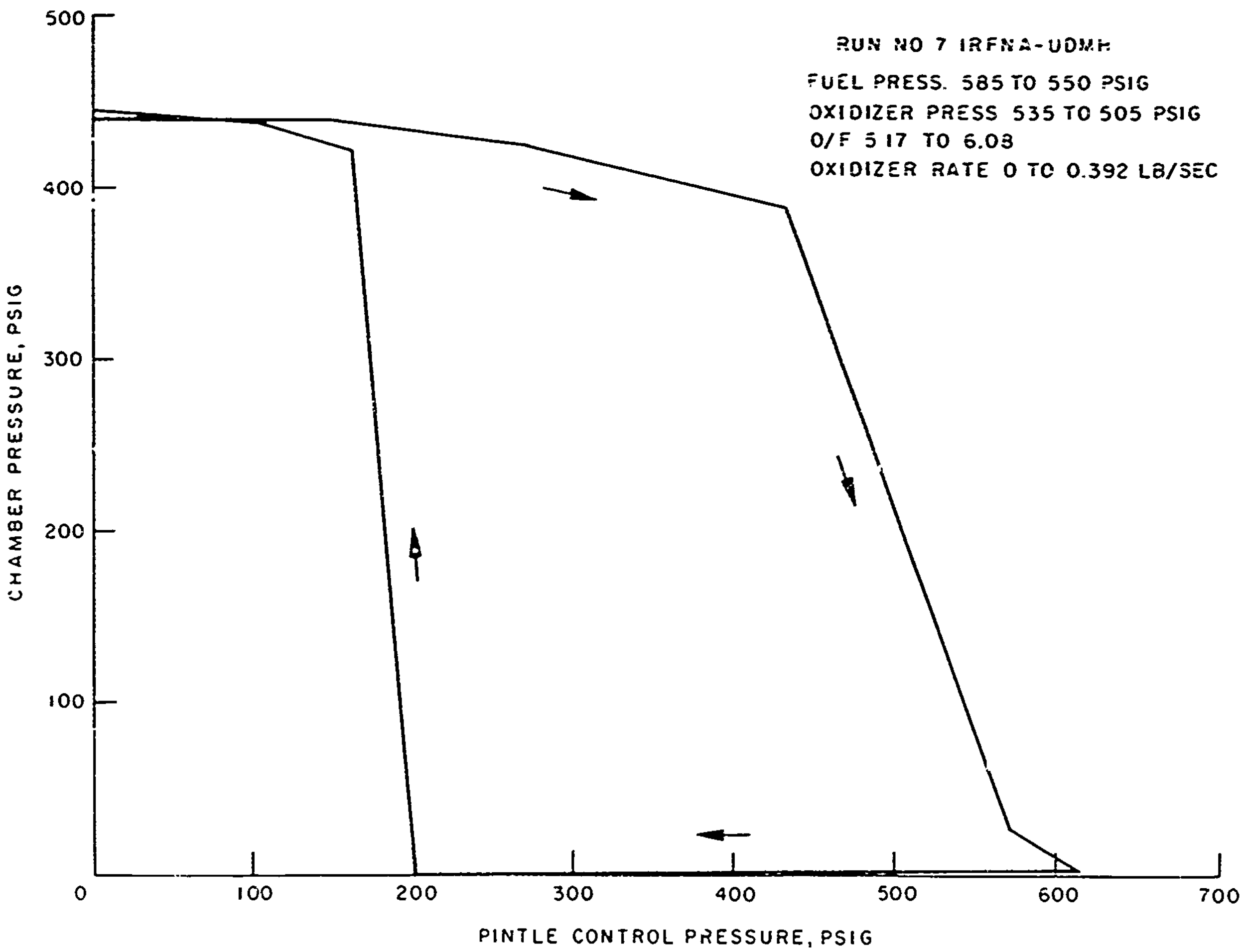


FIG. 26. Experimental Performance of Control Pressure Versus Chamber Pressure.

4. Following four preliminary water expulsion tests, two RFNA expulsion tests were conducted on directly pressurizing a tank 70% filled with 129 lb of RFNA and running the gas generator with an O/F ratio of 10:1 to 10.5:1 (Fig. 27). The expulsion tests consisted of the self-pressure regulating variable-demand liquid gas generator being fired into the top of a tank and expelling propellants through an outlet orifice. The tank was 10.750 inches in diameter by 44 inches long, with a wall thickness of 0.375 in. and two pyrex windows 90 degrees apart (at same level). The chemical reactions between the hot gases generated by the gas generator and the RFNA surface were photographed by a high speed camera and light source placed in the widnows. To vary the flow rates, the orifice size in the exit line was changed and a 200-psi burst disc was replaced for each run.

The instrumentation consisted of five pressure transducers and five thermocouple probes equally spaced longitudinally to measure internal tank pressure and temperatures. Two thermocouple wires were tack welded to the outside of the tank wall to measure the outer tank surface temperature.

The data showed that for the full 30 seconds of expulsion of RFNA from the tank, the self-regulating gas generator was capable of maintaining a constant tank pressure of 334 ± 15 psig without any violent chemical reactions. The chemical reaction varied with gas injection from the top of the tank, and was probably due to the lowering of the liquid impinging surface as the liquid was expelled from the tank. The maximum tank pressure was 334 psig, maximum tank temperature recorded was 245°F, and maximum outside tank wall temperature was 225°F. The recorded maximum outside tank wall temperature of 225°F for thermocouple T_6 was the same distance of 5 inches from the gas generator as thermocouple probe T_1, which did not record any temperatures for either test. Thermocouple probe T_2 was 10 inches below T_1; therefore this would account for thermocouple T_6 (outside tank wall temperature) being 225°F and almost the same temperature as thermocouple T_2 (tank temperature) of 245°F. Figure 28 shows the constant tank pressure curves of the RFNA expulsion test tank tests. Figure 29 shows the location of the thermocouples and Fig. 30 shows the temperature curves of the RFNA expulsion test tank tests.

With the completion of the expulsion tests, the Packrat II gas generator feasibility demonstration program was completed.

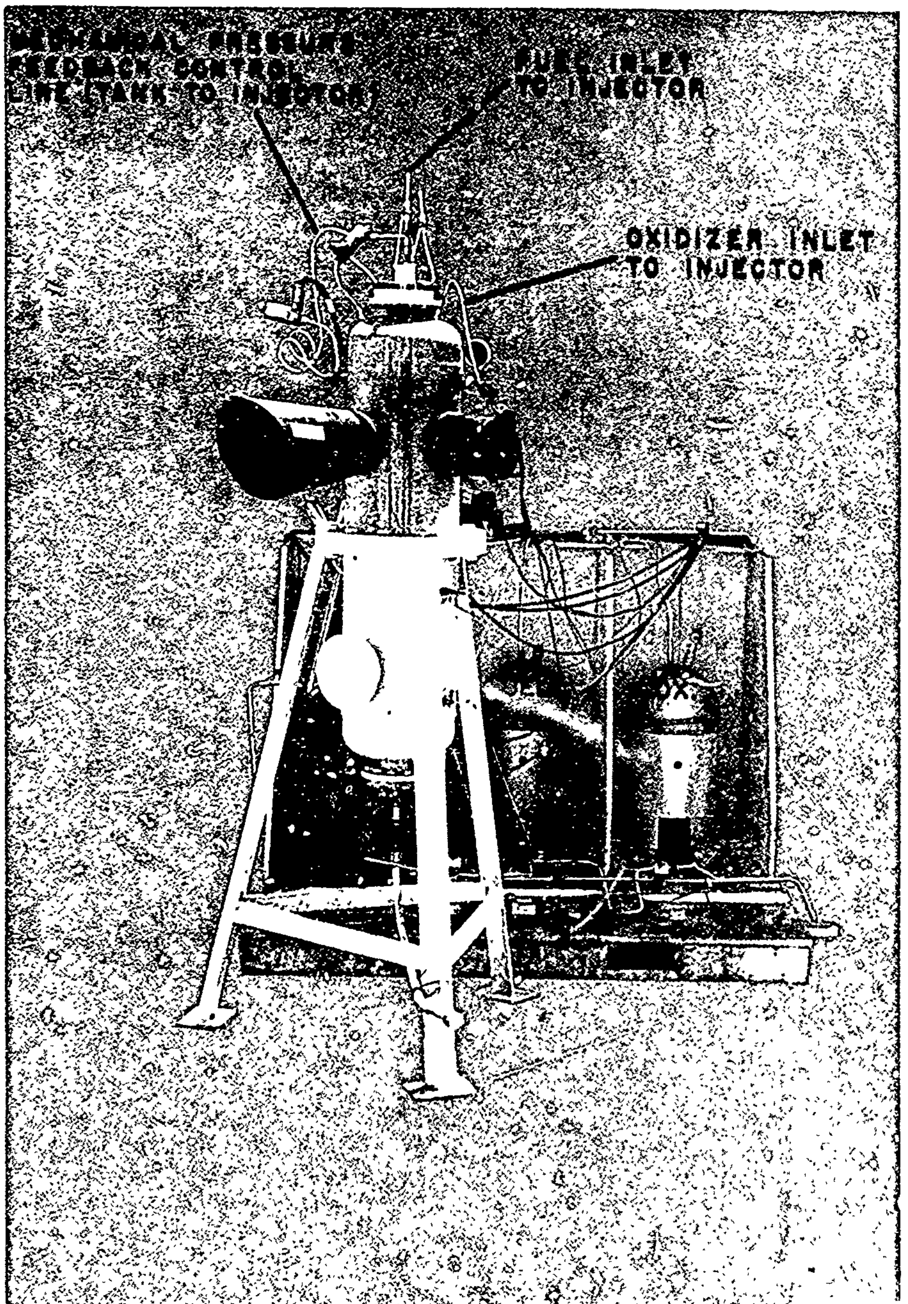


FIG. 27. RFNA Propellant Expulsion Test Tank Setup.

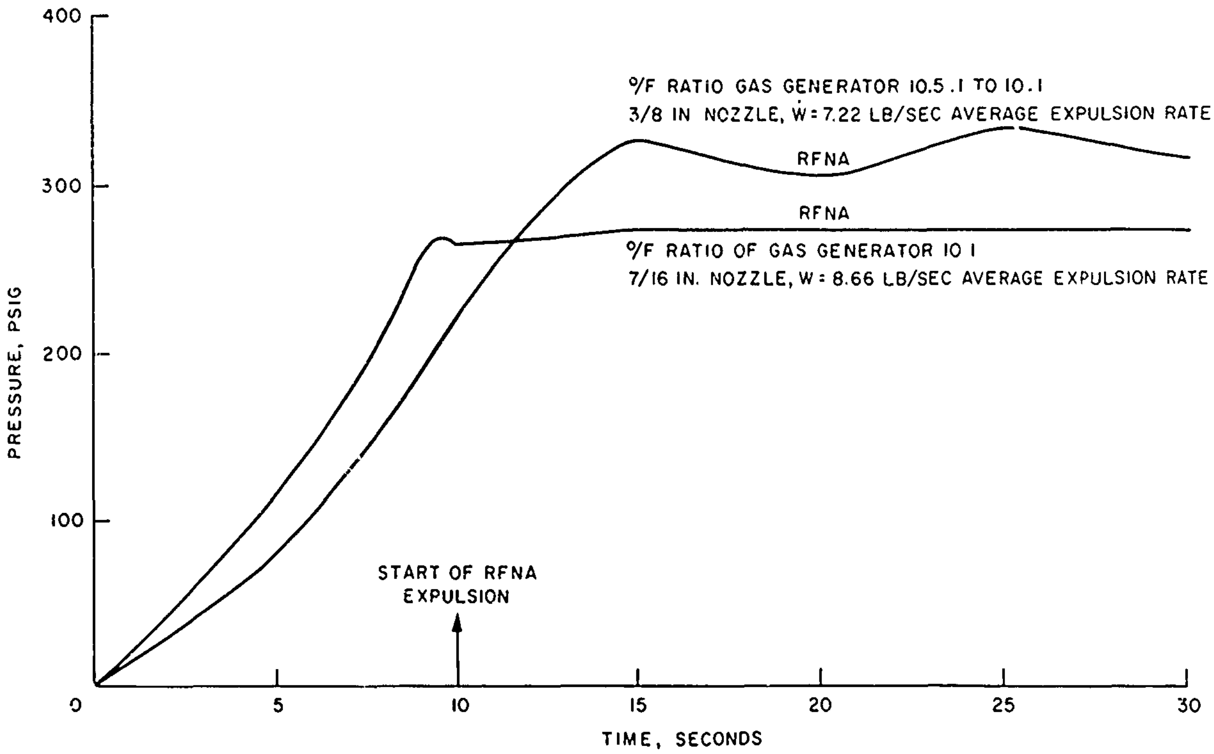


FIG. 28. Experimental Pressure Curves of the RFNA Expulsion Test Tank Tests.

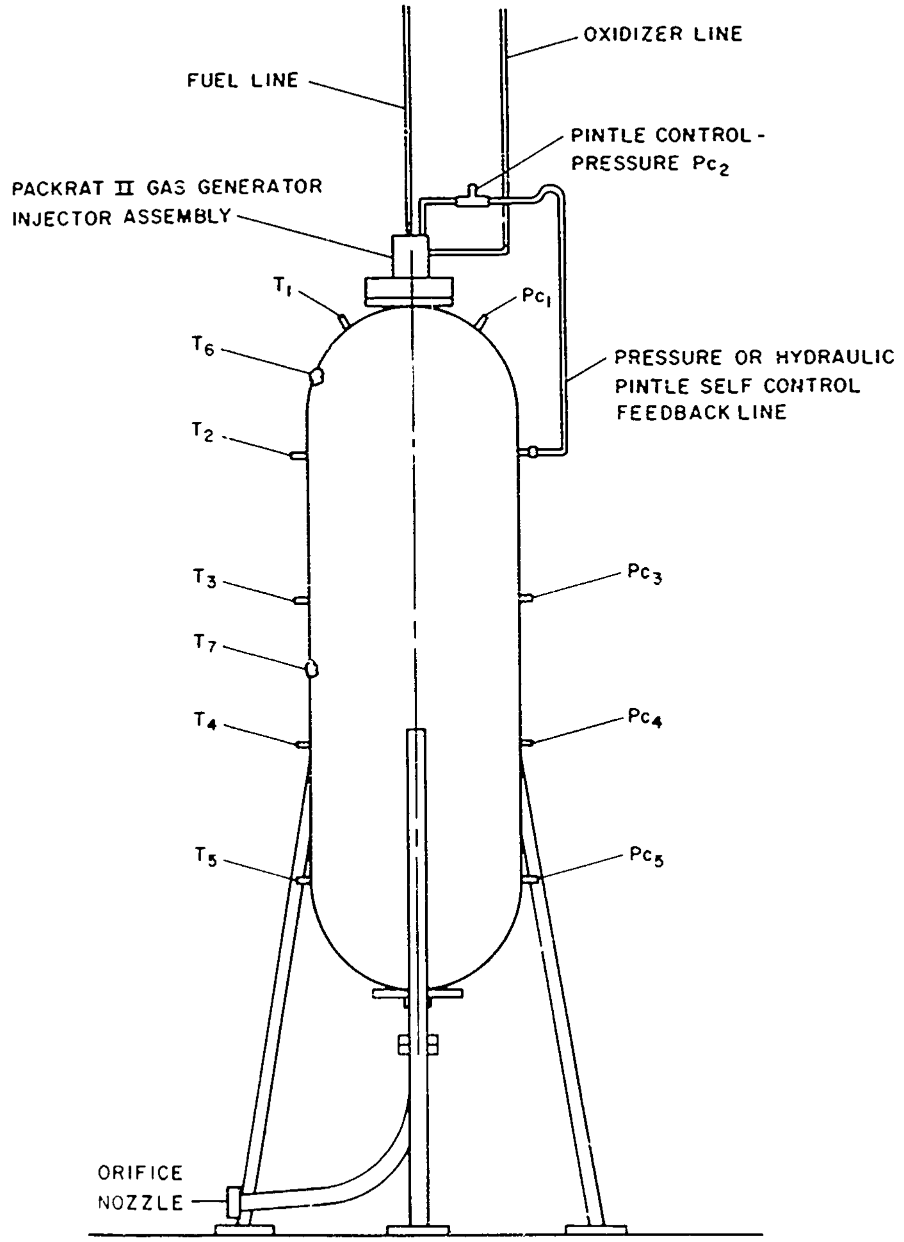


FIG. 29. Location of Thermocouples and Pressure Tranducers in RFNA Propellant Expulsion Test Tank.

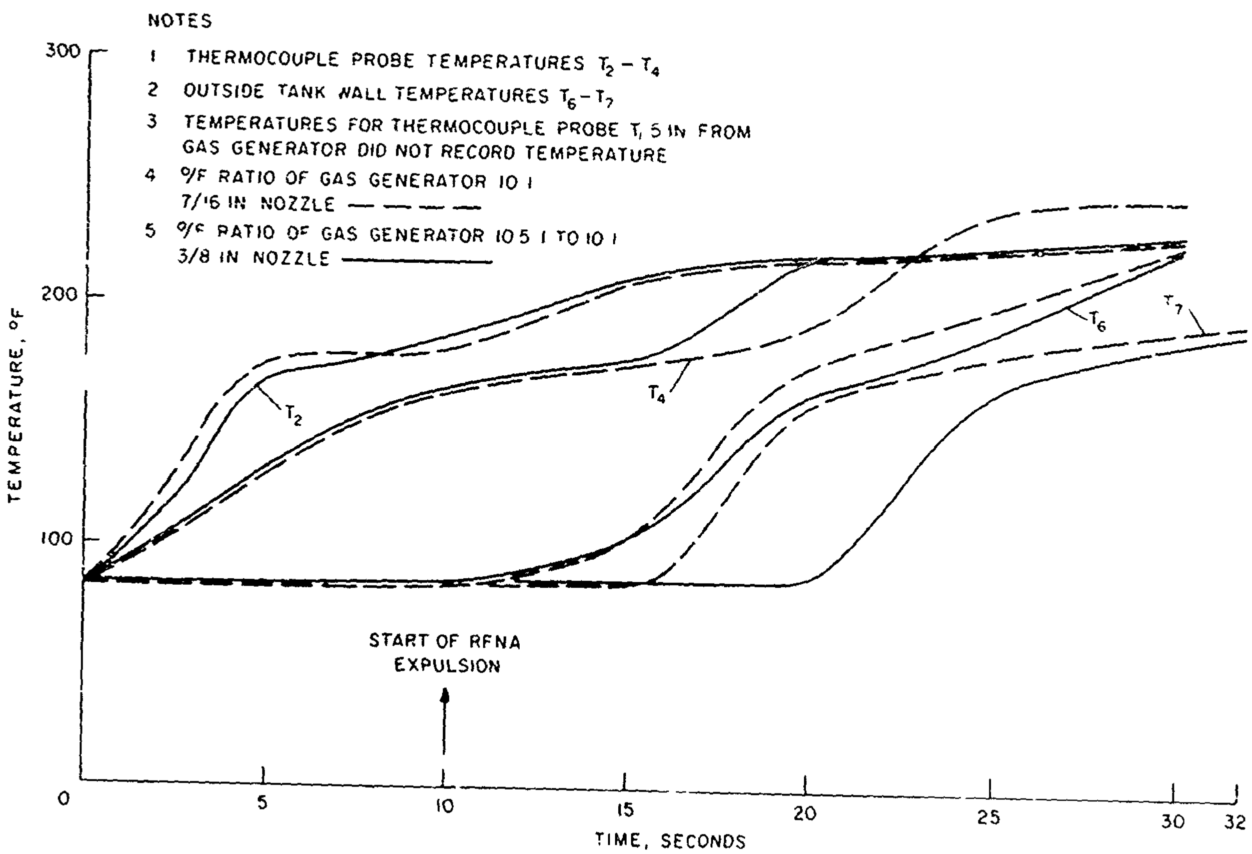


FIG. 30. Experimental Temperature Curves of the RFNA Expulsion Test Tank Tests.

Appendix C

0-35-POUND VARIABLE DEMAND GAS GENERATOR PROGRAM

ADVANCED DESIGN 0-35-POUND GAS GENERATOR

The 0-35-pound variable-demand liquid-propellant gas generator is an advanced design which is defined here as an improvement over the Packrat II variable-demand liquid-propellant gas generator, such as having faster response, lighter weight, and is a sophisticated gas generator design. The 0-35-pound gas generator is a hydraulically actuated injector, where control is achieved by a servovalve which uses hydraulic oil or the fuel as the hydraulic fluid, and was designed as a research and experimental development gas generator (Fig. 31).

The gas generator pressurization system consists of four major components: (1) a variable area injector; (2) a water cooled combustion chamber; (3) a servovalve; and (4) a pressure transducer as the feed-back signal.

INJECTOR

The injector assembly (Fig. 32) and injector assembly hardware (Fig. 33) consist of all parts fabricated from 300 series stainless steel, a pintle, ribbon orifice seat assembly, the body and aft support which form the external housing of the injector. The oxidizer enters the injector through a fitting on the side of the aft support and is ported through a passage in the center of the pintle to the inner annulus of the pintle. From this annulus, it flows outward radially as it splashes on the deflector plate. The fuel enters the outer annulus of the pintle through a fitting at the front end of the body, and is directed radially inward toward the splash plate as the pintle opens. The two propellants mix prior to entering the combustion chamber where additional mixing takes place and complete combustion occurs. An exploded view of the injector assembly hardware is shown in Fig. 34.

PINTLE

The pintle is designed to simultaneously regulate the flow of oxidizer and fuel, through its outer annulus for the fuel, and inner annulus for the oxidizer. The pintle is a hydraulic actuated piston which acts as a metering valve for the variable-area injector, and is positioned by an electro-hydraulic servovalve output acting on it. It is designed so that a linear displacement transducer can be attached to the aft end to measure the pintle position at any point of the full travel (0.025 inch).

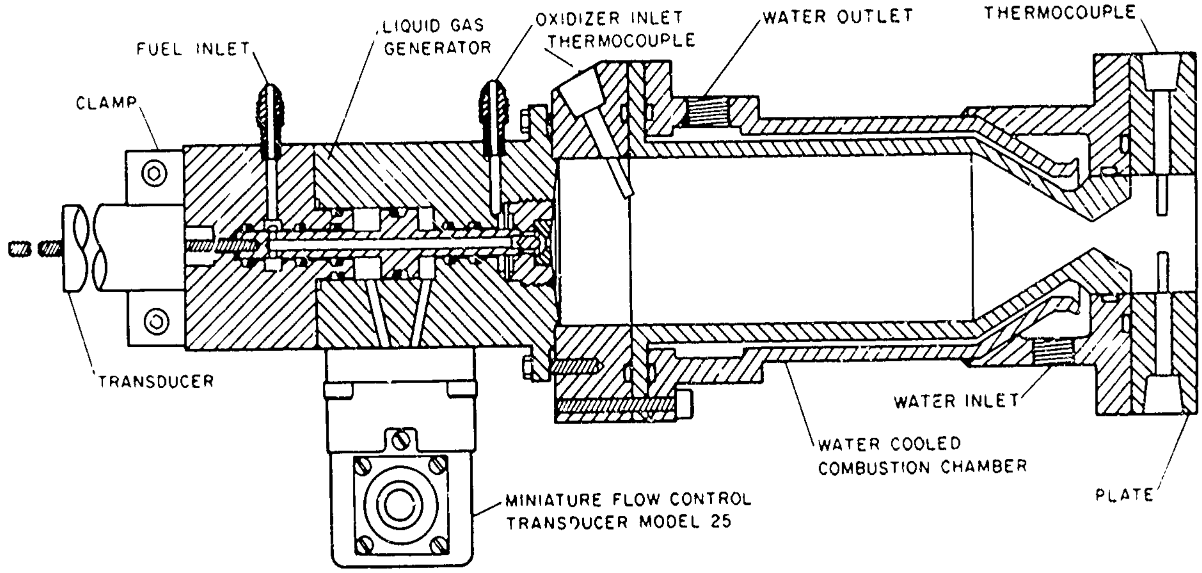


FIG. 31. 0-35-Pound Gas Generator Static Assembly.

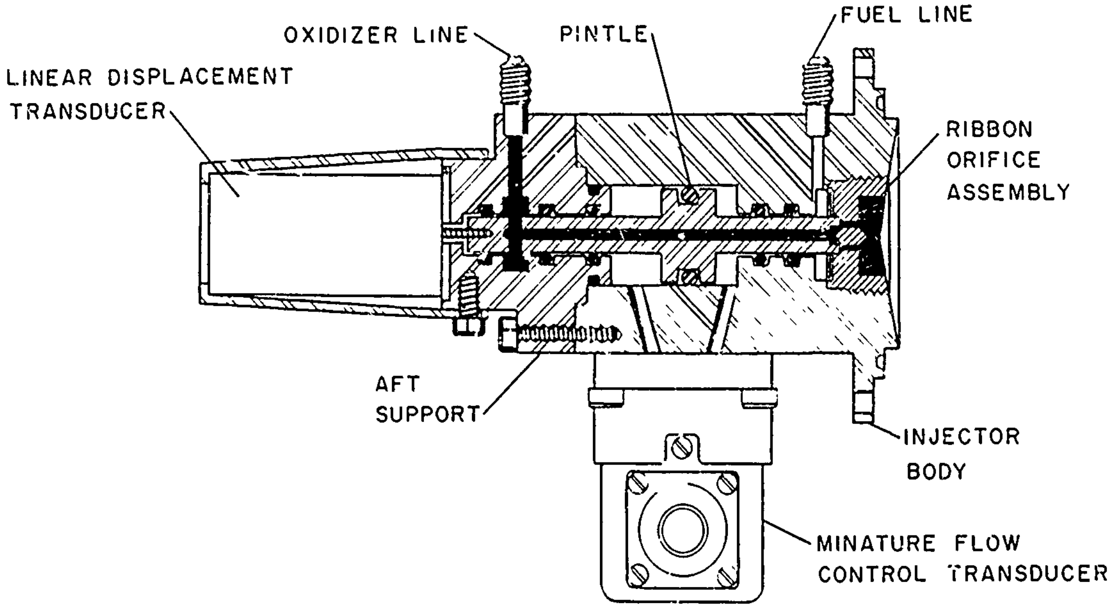


FIG. 32. 0-35-Pound Gas Generator Variable-Area-Injector Assembly.

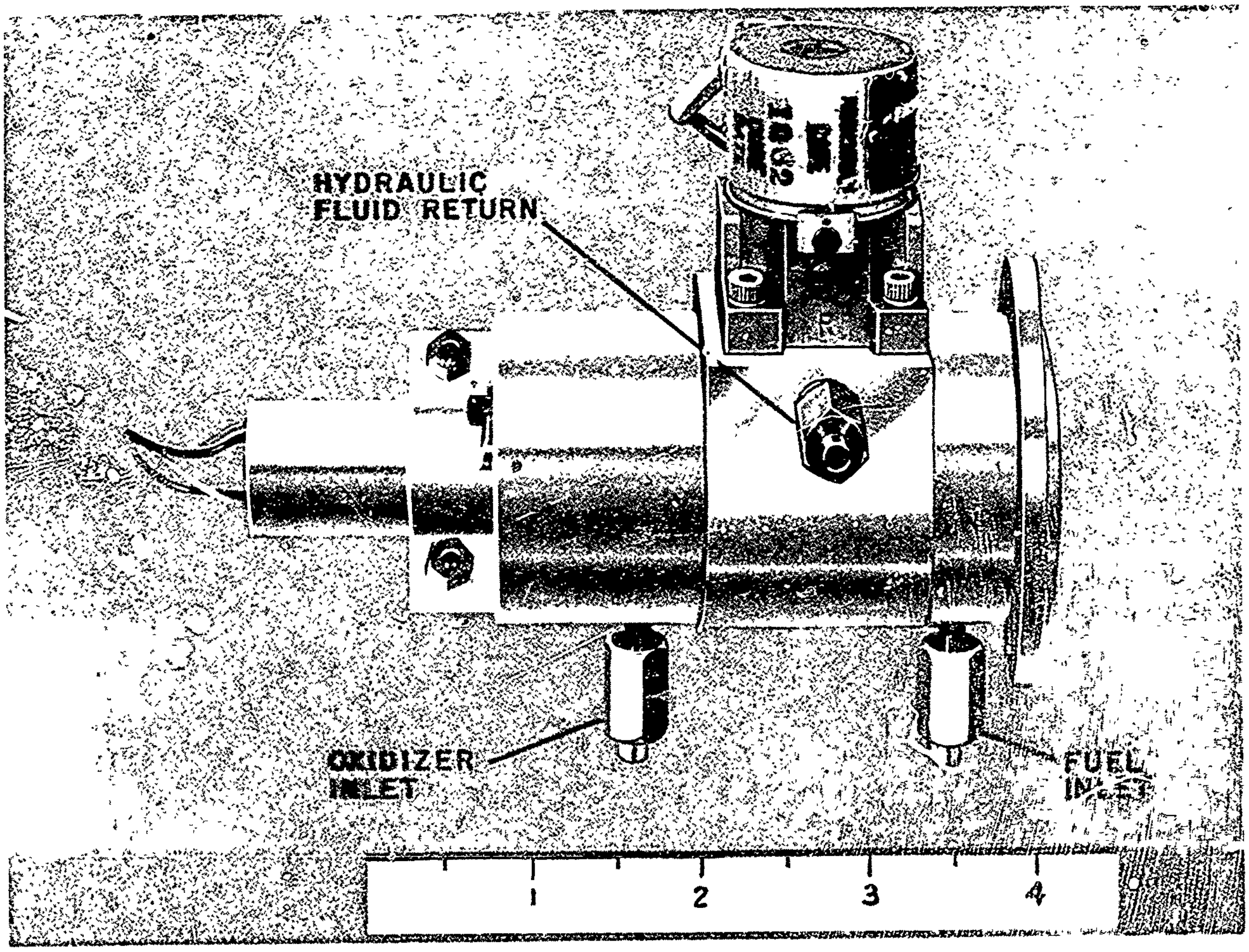


FIG. 33. 0-35-Pound Gas Generator Variable-Area-Injector Assembly Hardware.

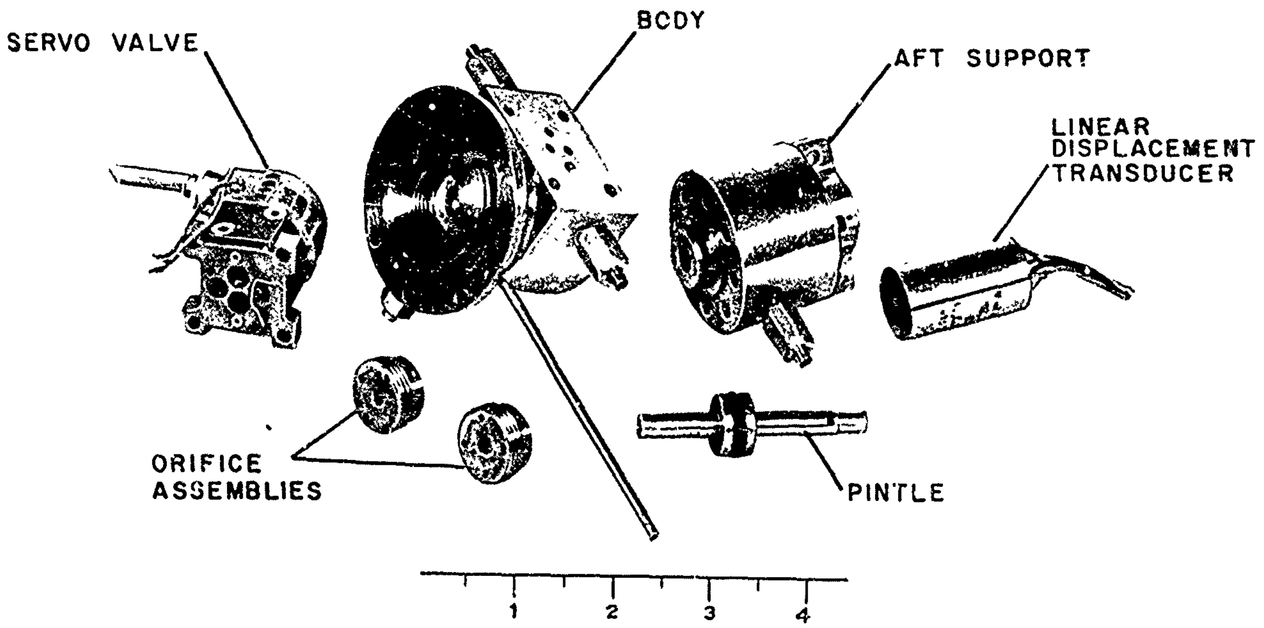


FIG. 34. Exploded View of Variable-Area-Injector Assembly Hardware.

ORIFICE SEATS

The ribbon orifice seat assembly not only provides both the oxidizer and fuel annular orifice seats for the pintle, but also provides the splash plate which is located at a point to improve propellant mixing, and to accelerate the burning action of the hypergolic propellants. The ribbon and conical orifice seat assemblies (Fig. 35-36) were investigated and the designs patterned after those designed for the 0-35-pound thrust motor. The ribbon orifice seat design had four fuel and four oxidizer slots. The flow, instead of flowing annularly around the pintle to the splash plate, was divided into separate streams emerging from rectangular shaped orifices. This improved the size restriction in tolerances on the pintle-orifice seat diameters, movement, orifice angles, and sealing characteristics The ribbon orifice seat assembly proved to be the better of the two in preliminary performance tests due to the better design and closer machining tolerances that the manufacturer was able to maintain.

INJECTOR BODY

The body contains four mating passageways for the hydraulic fluid to the servovalve which is attached directly on the side of the injector body. Two of the passageways are for accurately positioning the pintle, the third for supplying the hydraulic fluid to the servovalve, and the fourth for returning the hydraulic fluid to the supply tank or dumping overboard.

AFT SUPPORT

The aft support is designed so that a linear displacement transducer can be mounted onto the aft end of it, and at the same time be attached to the aft end of the pintle to measure pintle position travel from 0 to full open. Although the linear-displacement transducer was intended only for determining the transfer function of the motor and pintle position in the servo laboratory analysis and static firings, it can be used as an alternate feedback control system with the electro-hydraulic servovalve.

SEALS

O-rings made of synthetic rubber were selected as the seals. For the separation seal between the two fluids, a welded stainless steel bellows was also considered. Evaluation of both sealing methods indicated that while the bellows offered zero leakage and zero frictional characteristics, the inherent size, configuration, and difficulty in fabricating did place a restriction on its application. The O-ring seal

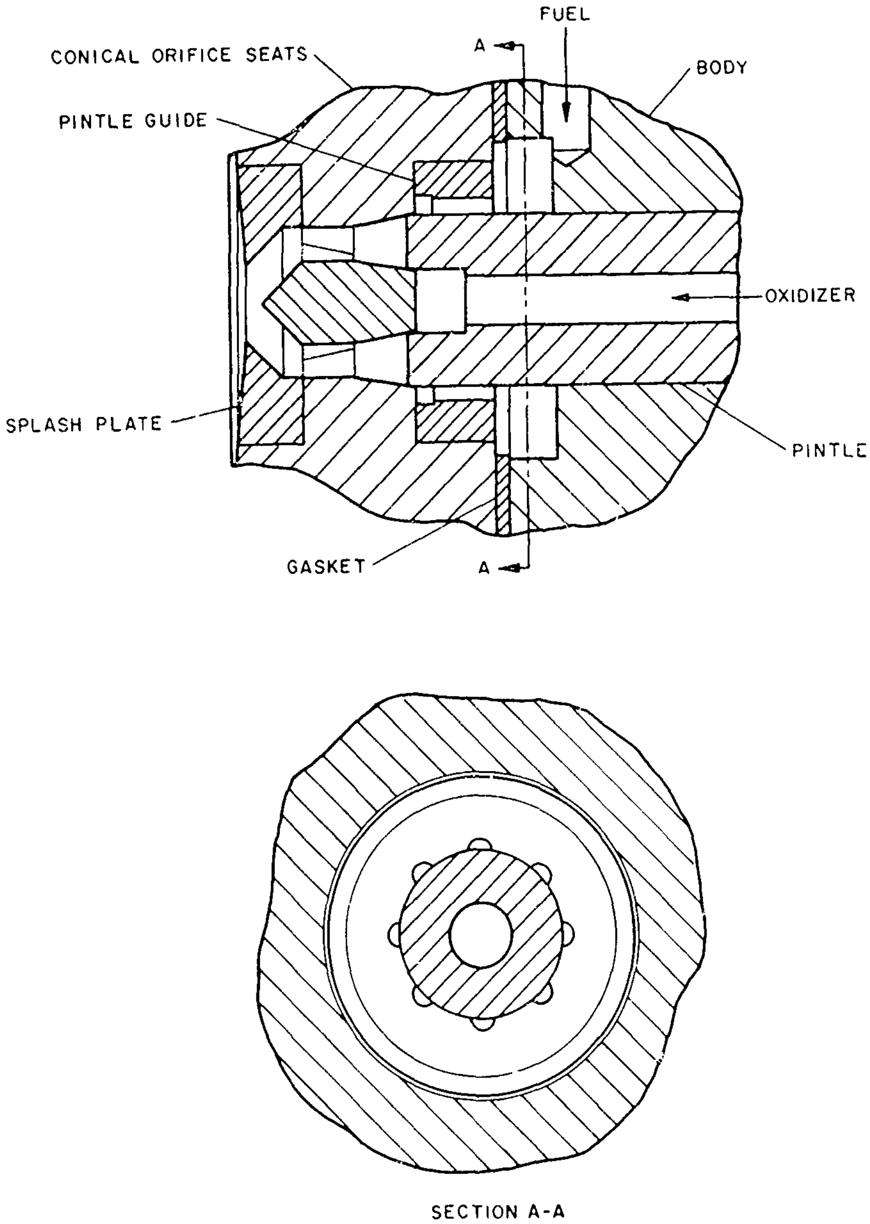


FIG. 35. Conical Type Orifice Seats.

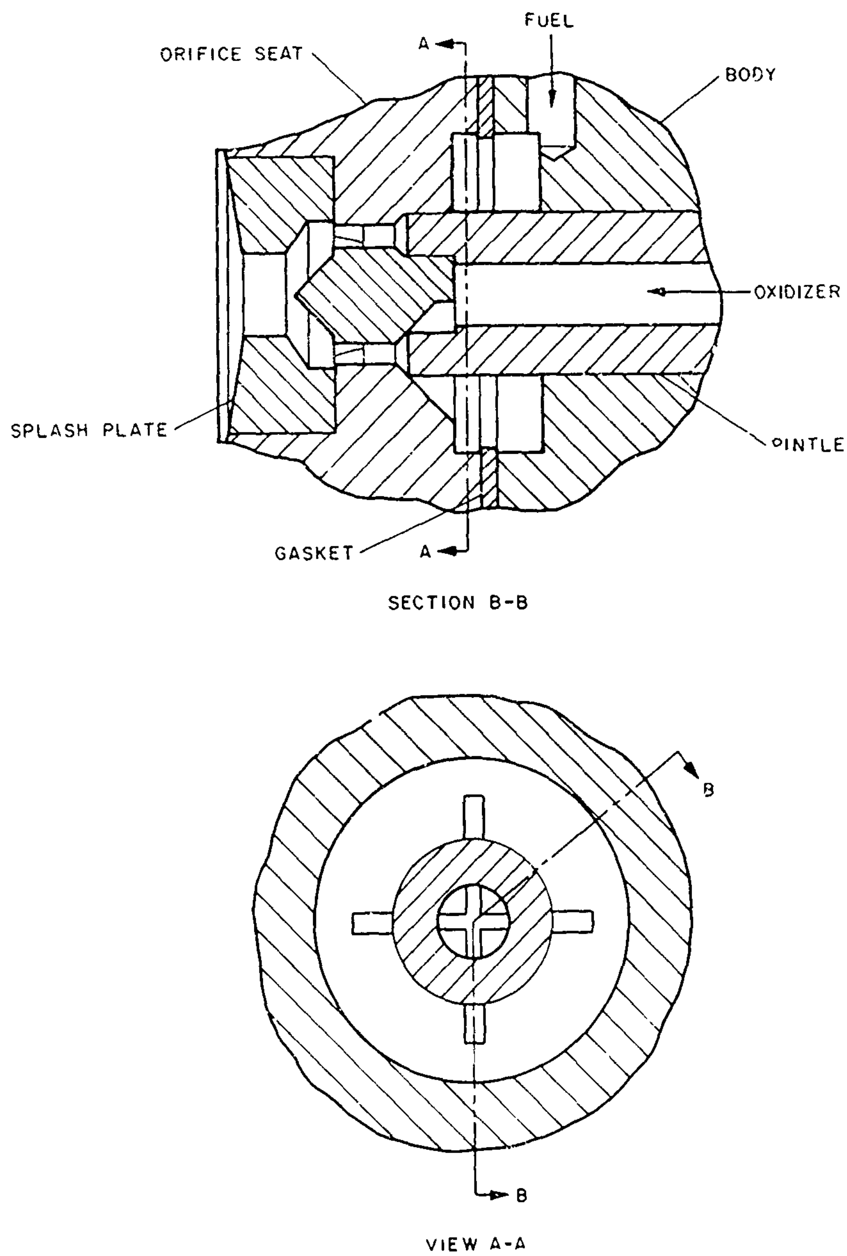


FIG. 36. Ribbon Type Orifice Seats.

offered a much smaller over-all package, and ease of fabrication and assembly. The chief leakage concern was that of the possible combining of the two hypergolic propellants. In order to prevent this, a double O-ring seal was provided. It was also required to have a vented orifice between the seals to eliminate the combining of the two propellants if a slight leakage occurred. O-ring materials were selected on the basis of propellant compatibility and aging properties.

COMBUSTION CHAMBER

A water-cooled combustion chamber was designed as static-test chamber hardware. The chamber performed as designed and allowed long-duration tests to be made without failure of the combustion chamber or severe throat erosion.

The combustion chamber was designed to have a copper liner, stainless steel jacket, and two stainless steel spacers. One of the spacers was placed between the injector and the combustion chamber so that two thermocouple probes could be mounted on it to measure the combustion temperatures inside. The second spacer was attached to the aft end of the chamber so that thermocouple probes could be mounted on it to measure the exit combustion temperatures as they left the chamber.

A copper liner was designed and fabricated for a combustion chamber pressure of 600 psi, an L^* of 250 inches, a 0.177-inch nozzle diameter, and a C_F of 1.267.

SERVOVALVE

The electro-hydraulic servovalve or flow control transducer controls the application of hydraulic fluid supply pressure to either side of the actuator-pintle to position the pintle with respect to the variable-area annular orifices and thus regulate propellant flow. A Hydraulic Research & Mfg. Electro-Hydraulic Servovalve Model No. 251210 was used for both the servo laboratory analysis and static firings.

TRANSDUCERS

An Alinco pressure transducer was used for the combustion chamber pressure feedback signal, which had a pressure range of 1,000 psi. A G. L. Collins Linear Displacement Transducer, Model No. SS-203, was used for two different applications. The first application when used with the chamber pressure transducer as the feedback signal was used only for measuring and calibrating pintle position throughout pintle travel. In the second application the linear-displacement transducer was used as a pintle position feedback signal.

INSTRUMENTATION

The propellant flow rates were measured by two Potter turbine-type flowmeters in each propellant line as an added check on the flow rates. Standard Control flowmeters were used in an attempt to measure the extremely low flow rates of 0. 133 gpm more accurately than the Potter flowmeter, but were unsuccessful.

The hydraulic line, propellant injection, and combustion chamber pressures were measured by Alinco pressure transducers.

The temperatures for the combustion gases inside the chamber and the gases leaving the chamber nozzle were measured by Aero Research Aeropak, chromel-alumel type thermocouples.

CONTROL SYSTEM OPERATION

The electro-hydraulic servo control system operates when an input signal to the servo amplifier from the pressure transducer (to increase the combustion chamber pressure) sends an error signal to the servovalve tending to open the pintle The pintle then moves to allow an increase in propellant flow. The resulting increase in combustion chamber pressure then creates an increase in the pressure transducer electrical signal fed back to the servo amplifier. This feedback signal then cancels out the input signal and reduces the error signal to the servovalve to zero. With no input signal, the second stage spool of the servovalve then centers and stops the movement of the pintle. The over-all effect would be an increase in combustion chamber pressure for an increase in electrical signal. Following the same principle, a decrease in the electrical signal would produce a decrease in the combustion chamber pressure.

Figures 37-39 shows the servo system, servo electronics, and command box used for the third series of static tests. A similar control system was used for the first and second series of static tests. Figure 38 shows a voltage divider center tapped to ground, which was placed across the servovalve excitation leads. This was done to reduce the common mode voltage on the servo current read-out from about 300 volts to about 20 volts. The reason for reducing the voltage from 300 to 20 volts was mainly to eliminate possible damage to the electronic equipment used, and to eliminate any possible accidental touching of this voltage line by the personnel; this was not intended to affect the control system. The pintle position feedback was put through a gain of one galvo driver so as to not load the linear-displacement transducer.

The command box (Fig. 39) was adjusted to give signals equivalent to ten one-hundred-psi step settings. This was calibrated, using

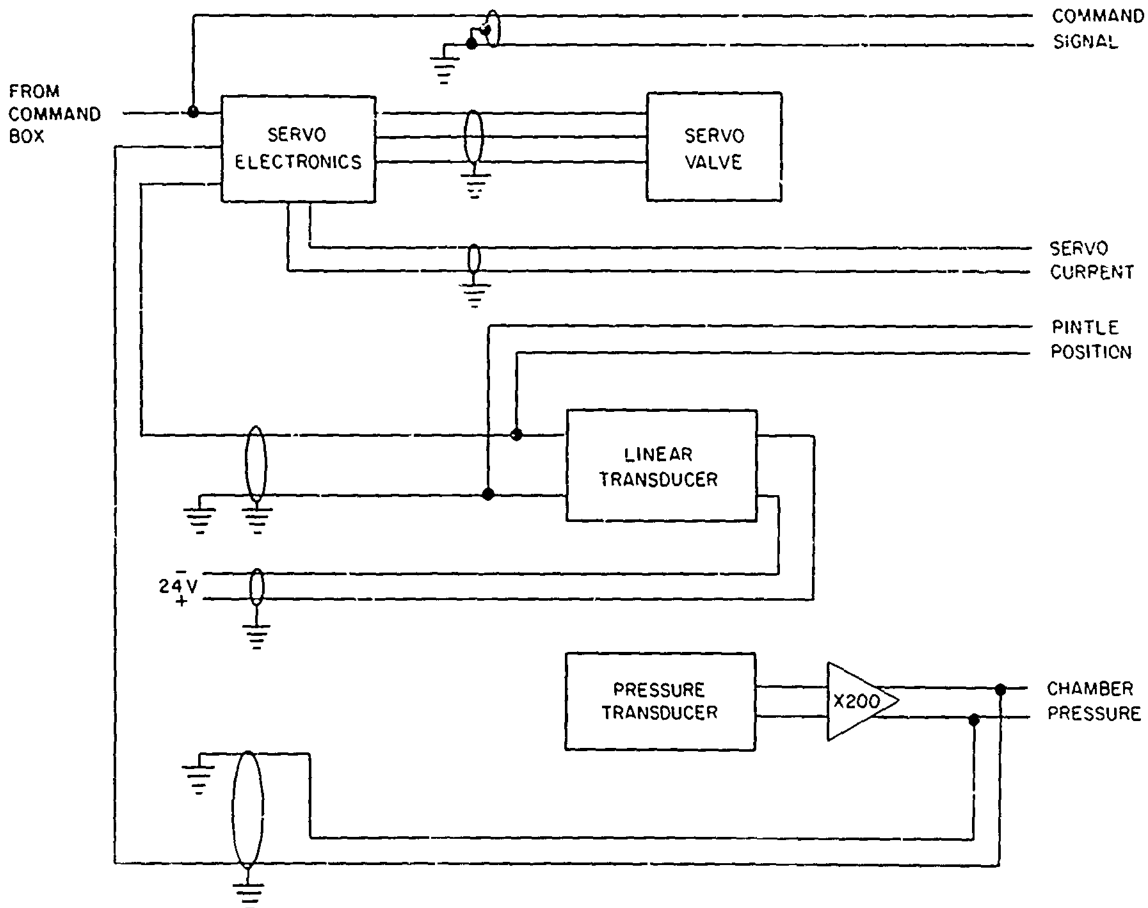


FIG. 37. Servo System Block Diagram.

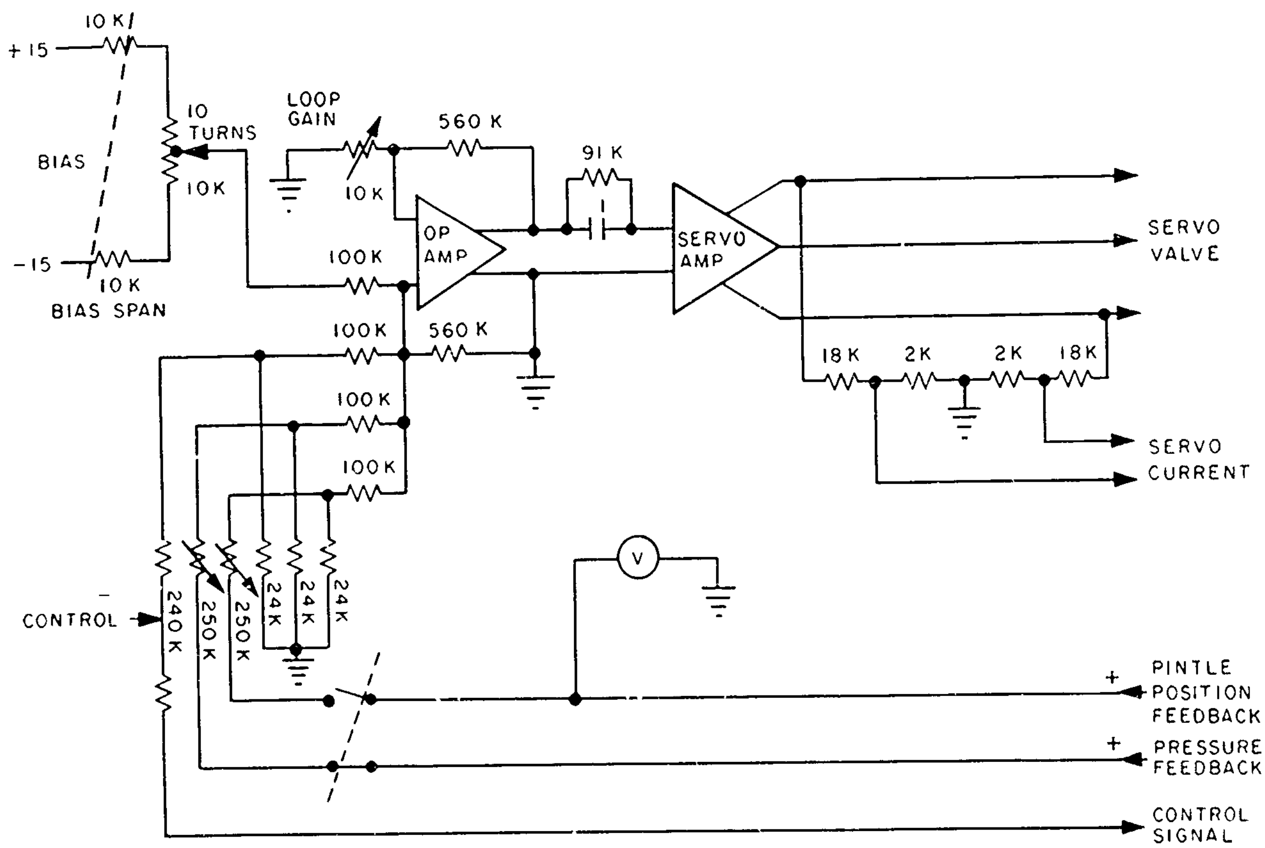


FIG. 38. Servo Electronics Schematic.

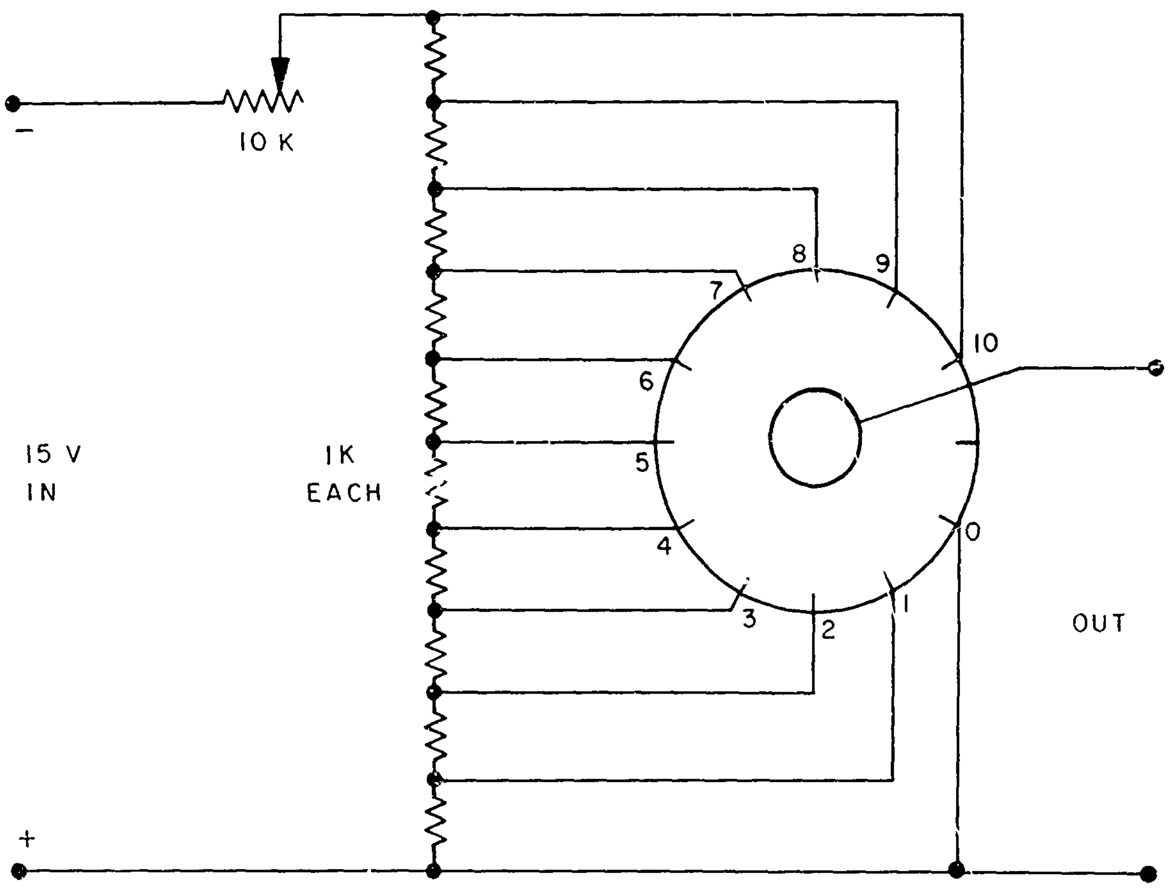


FIG. 39. Command Box for Pressure Control Settings.

delta R calibration equivalent to 300, 400, 500, and 600 psi. A negative command signal would open the servovalve, and a positive feedback signal would hold the pressure at the combustion chamber pressures desired.

Two possible control systems for a liquid-propellant gas generator which may be used to pressurize a motor are a variable-demand liquid-propellant gas generator with a tank pressure-sensing transducer feedback (Fig. 40), and a preset pressure-regulated liquid-propellant gas generator (Fig. 41) with a tank pressure-sensing switch preset for a certain pressure to turn on or off two upstream solenoid valves or a bipropellant valve. The control system with the pressure-sensing switch could either have a centromix injector or a variation of a solenoid actuated variable-area injector for the gas generator, if desirable (Fig. 42).

SERVO LABORATORY TESTS

In order to evaluate the gas generator design characteristics and electro-hydraulic control system, a series of dynamic and static tests were performed in the control systems laboratory.

In dynamic characteristics, this system was similar to others of this type in that it could be made to oscillate at high values of loop gain, exhibit a considerable non-linearity during large excursions, and was adversely affected by increasing loads on the actuator output. Compensation in the form of a lag network (Fig. 43) was used throughout these tests to reduce servo loop instability and increase the value of loop gain which could be set into the system.

Most of the investigation was carried out using feedback from the linear-displacement transducer attached to the actuator-pintle. Non-linearity occurred when large signals (greater than half of full pintle travel) were applied to the system; distortion in the form of extreme slope changes was found to exist at all but the lowest and highest frequencies. Open loop tests showed the distortion to be in the servovalve-actuator response. When using small signals at excursions of 0.001 inch or less, the non-linearity disappeared and it was possible to run a frequency response test on the system. The results of this frequency response test are plotted (Fig. 44) in the form of a closed loop amplitude ratio plot.

Attempts to close the loop, using simulated chamber pressure feedback in the laboratory, resulted in a system which was difficult to operate and control. This was due to the non-linearity of the transfer function of pintle position to chamber pressure, when chamber pressure was simulated by a flow restriction downstream from the chamber. Past experience indicated that the transfer function from pintle position

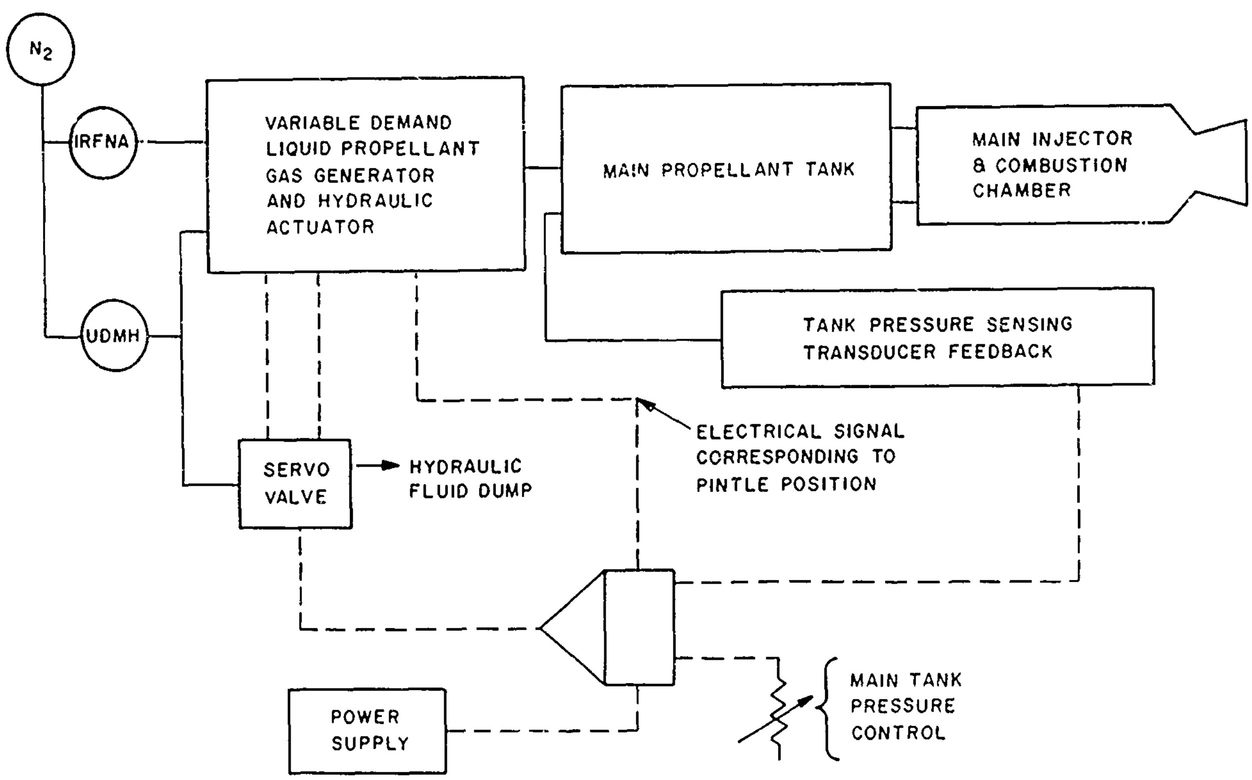


FIG. 40. Control System Using a Pressure Sensing Transducer for a Variable-Demand Gas Generator.

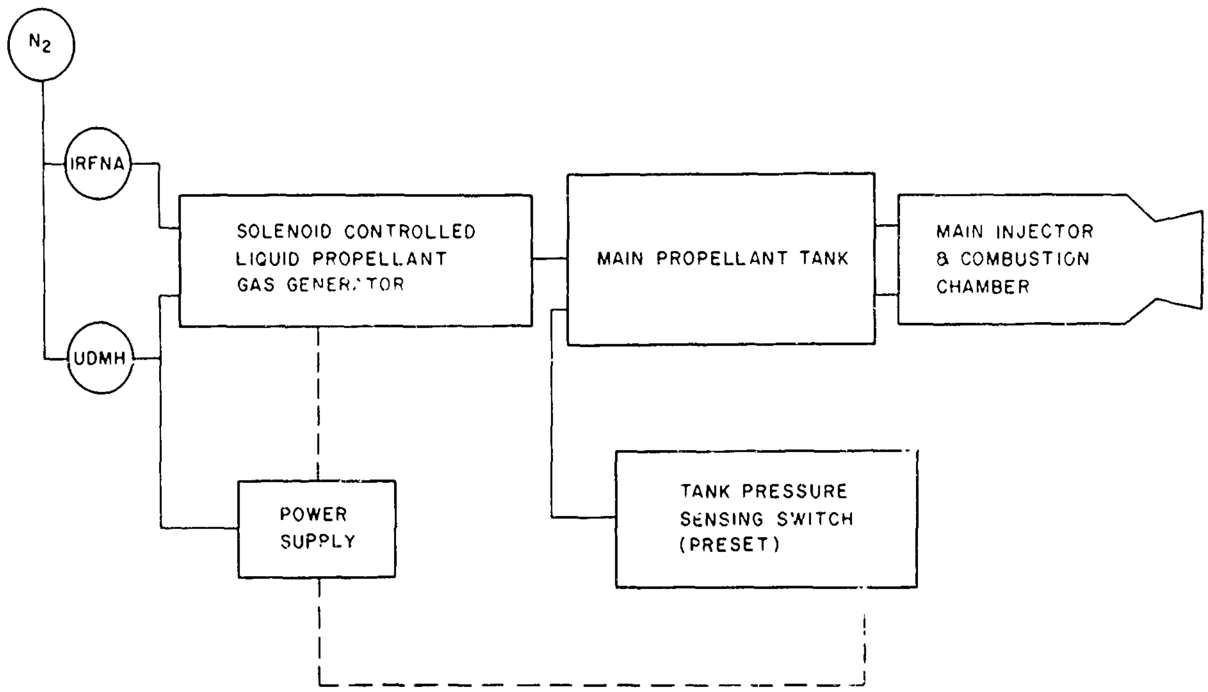


FIG. 41. Control System Using a Preset Pressure Sensing Switch for a Variable-Demand Gas Generator.

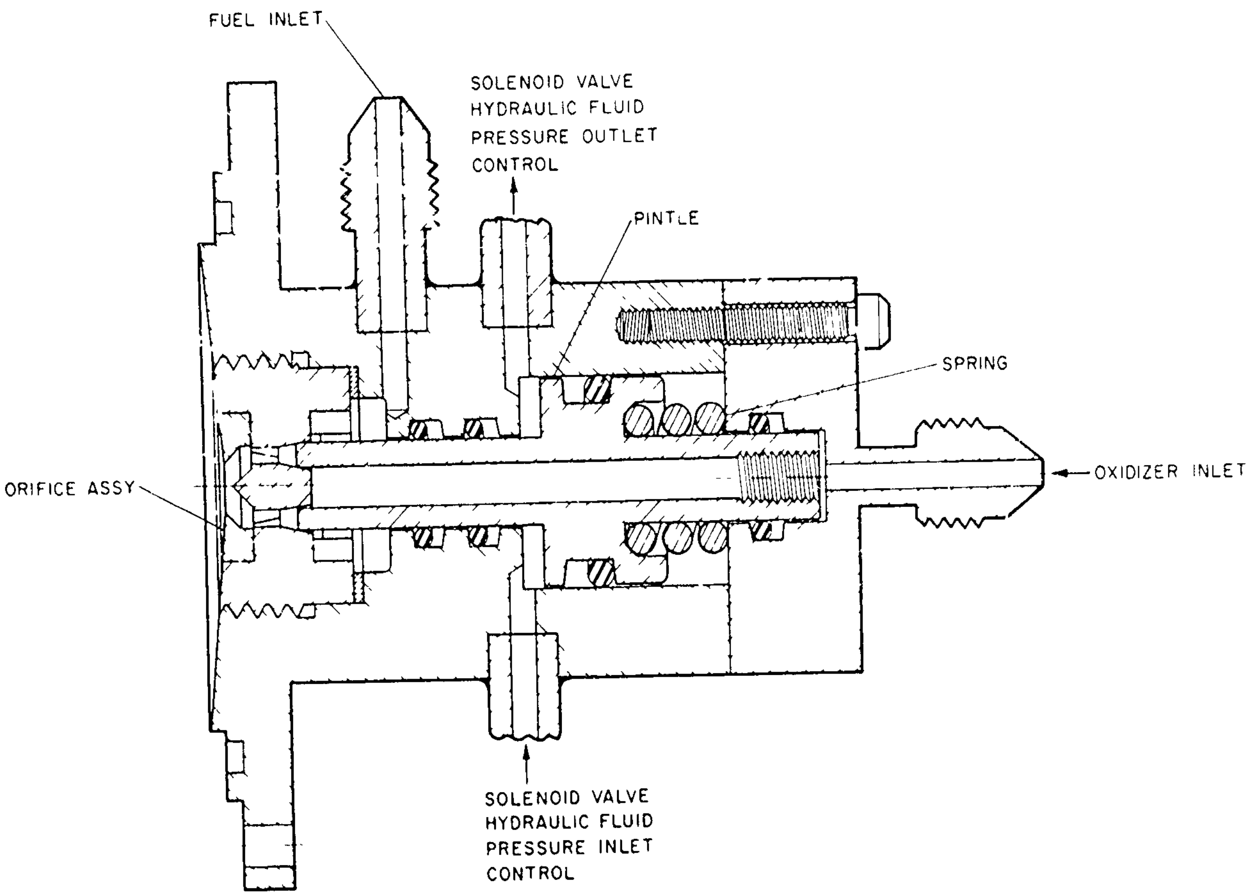


FIG. 42. Solenoid-Actuated Variable-Area-Injector Assembly.

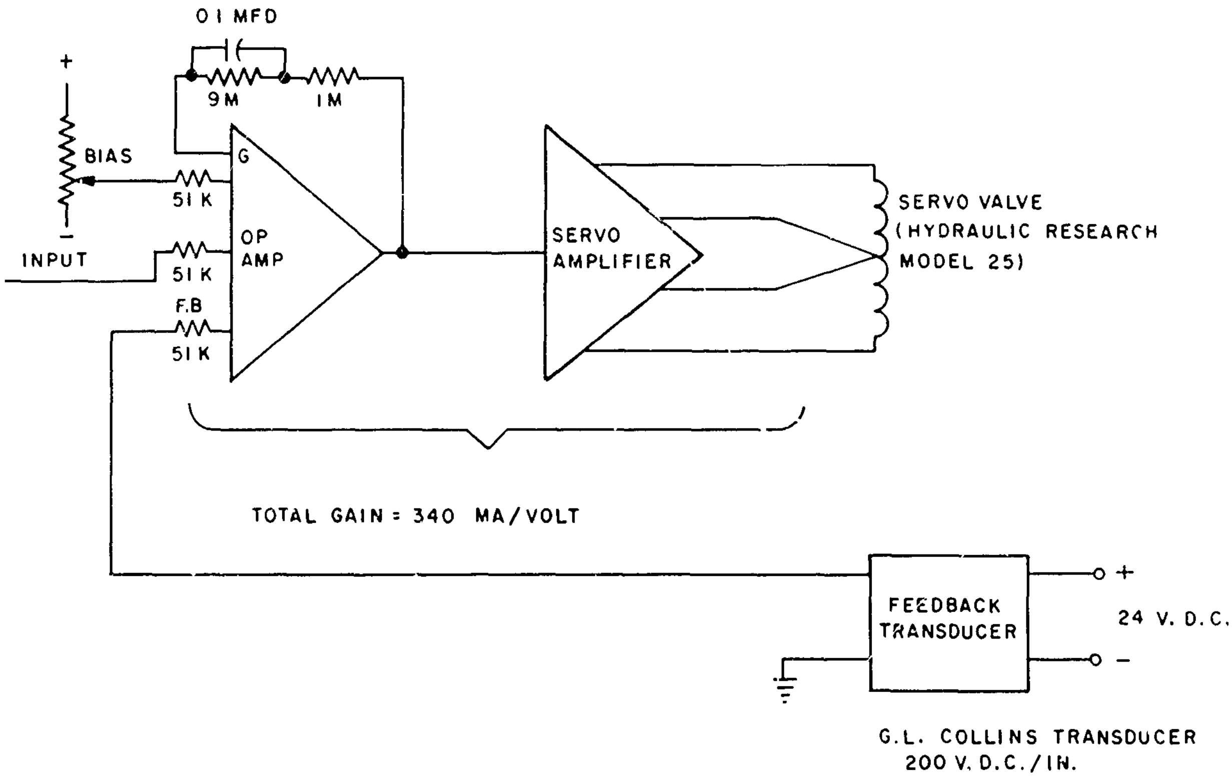


FIG. 43. Preliminary Servo Electronic Schematic Used in Servo Laboratory.

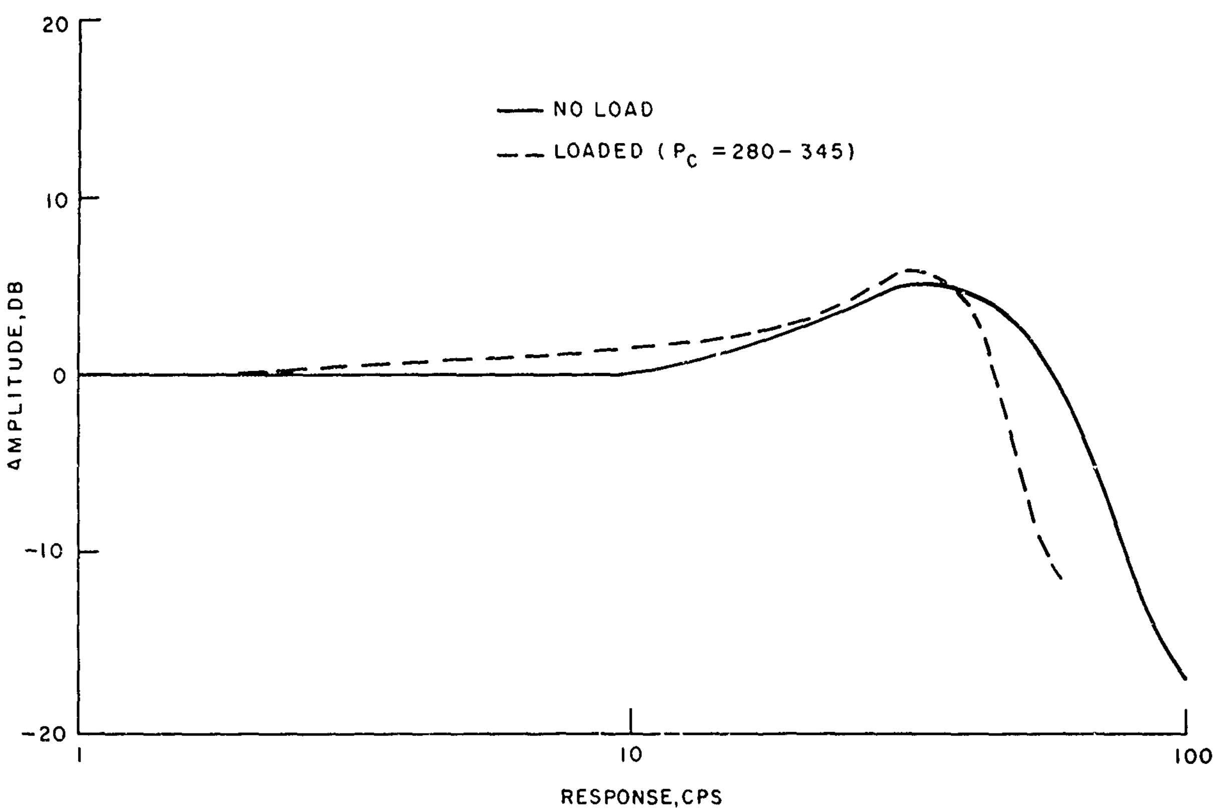


FIG. 44. Closed-Loop Frequency Response Tests.

to chamber pressure in a burning motor would be much more linear and the resulting control loop would be more stable. Response tests similar to those run for pintle position, using a linear-displacement transducer, were also run with the system loaded by chamber pressure, using a pressure transducer as a feedback signal. The results of these tests are also plotted in Fig. 44.

Also, static load tests were made to determine the static load forces acting on the actuator-pintle of the gas-generator injector. A pressure was developed within the combustion chamber as a result of propellant flowing into the chamber. These tests were run using simulated chamber pressure feedback and were set so that 600 psi would be developed within it when the propellant supply pressure was at 800 psi and the actuator pintle was in the open position of 0.025 inch. Figure 45 is a plot of the resulting load reflected to the actuator-pintle of the injector as it was cycled through a 0.018-inch stroke.

The primary static load as determined from these tests was due to the simulated chamber pressures. This load was unidirectional and non-linear. In general though, these tests showed that the present control system could accurately control the position of the injector pintle, under these simulated loads, when nearly steady-state control signals were applied to the control system. Further mechanical refinements of this control system were found to be unnecessary at the time if the pintle were positioned under nearly steady-state conditions. The difference in values for the forces required in opening and closing the actuator pintle was accounted for when the net forces derived from the tests were considered. Some allowance must be made for the lack of perfect agreement in these values (Fig. 45), since 1,000-lb gauges had t be used to measure these relatively low force (0 to 36 pounds force maximum) levels.

STATIC TESTS

Three test series for a total of seven static tests were performed, totaling about 3 1/2 to 4 minutes of operating time. The first of these three series used a linear-displacement transducer as the feedback signal for controlling the gas generator. The next two series used a combustion chamber pressure transducer as the feedback signal for controlling the combustion pressure.

The first static-test series controlled the gas-generator rate at the command step inputs desired and without any problems of controllability.

The second series of tests using the pressure feedback control system, encountered some difficulties with the noise in the system interfering with the low-level signals from the pressure transducer.

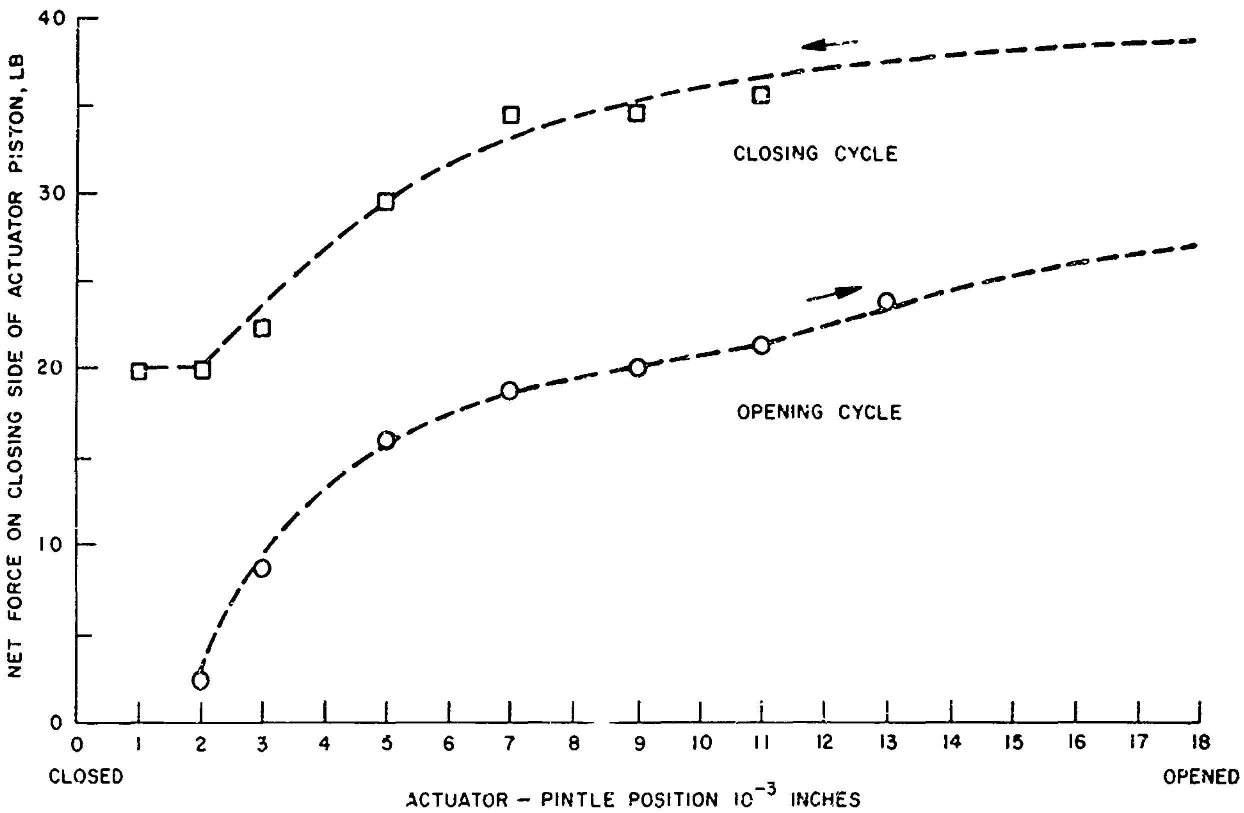


FIG. 45. Static Loads on Actuator-Pintle.

This problem was corrected by boosting the transducer signal from a D. C. amplifier. The results from these tests indicated that the servo system, although it functioned as commanded by inputs, did not have a high enough response and was on the threshold of instability. The servo system was modified before the third test series was run.

In the second test series the flowmeters, after operating in the higher flow ranges. did not return to their linear ranges and so some of the flow rates are questionable. During the second test the injector deflector plate or splash plate was blown out of the injector face. This did not appear to have any effect on the thorough mixing of the propellants for the rest of the test run. The gas generator, having a combustion chamber L^* of 250 inches, helped considerably in the thorough mixing of the propellant before leaving the chamber.

Figure 46 shows the combustion chamber temperatures as a function of W_T and O/F ratio for the second test series of static tests three and four.

The third series of tests responded more accurately than the second test series for command inputs, and maintained constant combustion pressures for settings of 325, 500, and 600 psi chamber pressures within ± 10 psi. The c^* efficiency for these tests and the second test series was low. They ranged from 1,300 to 1,700 ft/sec lower than the theoretical calculations for both the fuel rich mixture ratios of RFNA/UDMH, and RFNA/80% UDMH-20% H_2O. These c^* values would probably have been higher if an L^* of 250 to 400 inches had been used.

A thin coating of a carbonaceous material was found on the surfaces of the injector face and the combustion chamber after each test. This coating was more pronounced at the low mixture ratios with straight RFNA/UDMH than with water diluted UDMH. The presence of this carbonaceous material is substantiated by Table 5 which is the theoretical gas composition of RFNA/UDMH and RFNA/80% UDMH-20% H_2O. It shows the solid carbon in both combustion gases in the low mixture ratios.

The same injector assembly was used for all three test series, with no signs of erosion on the injector face, and a little erosion on the chamber nozzle.

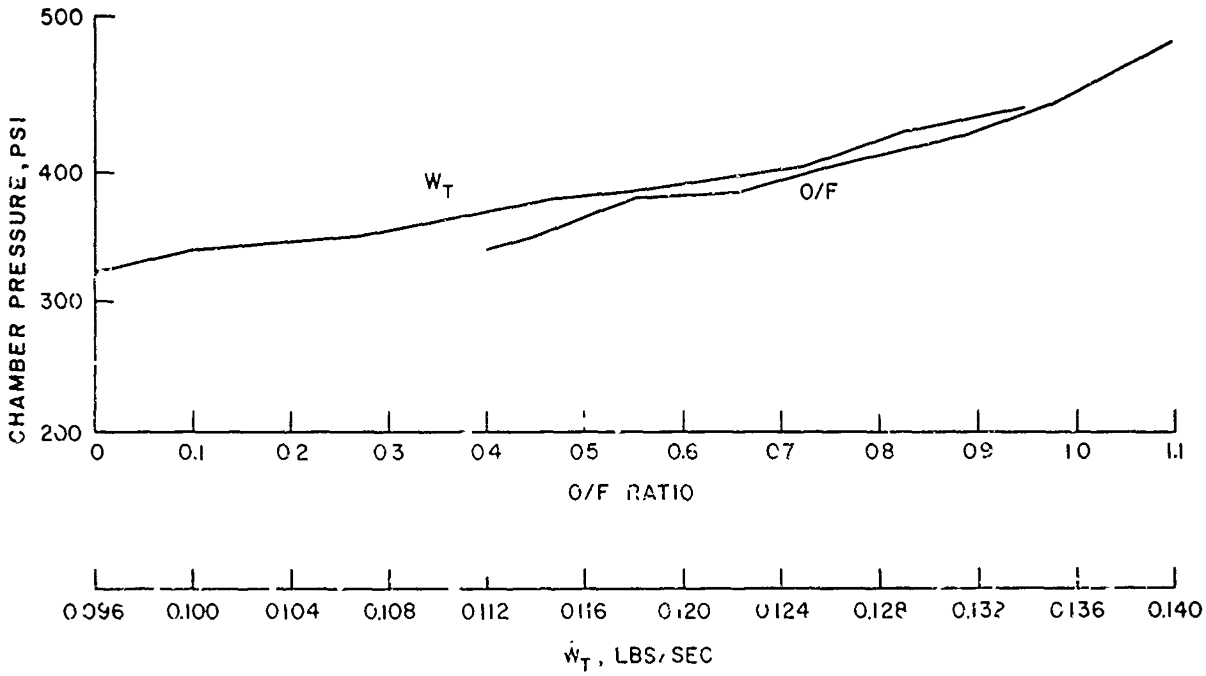


FIG. 46. Experimental Performance of RFNA (14% NO_2, 1.5% H_2O)/UDMH for Test Series 2.

TABLE 5. Theoretical Gas Composition, Mole Fraction of RFNA (14% NO_2, 1.5% H_2O) With UDMH, and 80% UDMH-20% H_2O at 600 psia

O/F ratio	CO	CO_2	C^*	CH_4	H_2	H_2O	N_2	NH_3	AAA
A. Propellant Combination RFNA (14% NO_2, 1.5% H_2O)/UDMH									
1.0	1.5447	0.1099	---	0.0093	3.0931	0.5905	1.2434	0.0020	6.1905
0.8	1.5720	0.0852	---	0.1930	3.2946	0.3488	1.2893	0.0042	6.0134
0.6	1.3804	0.0644	0.1381	0.4970	3.1841	0.2572	1.3468	0.0051	6.0601
0.4	0.9576	0.0531	0.6611	0.7043	3.2665	0.2833	1.4207	0.0065	6.0990
0.2	0.4734	0.0276	1.2044	1.0666	3.2661	0.2579	1.5194	0.0087	6.1655
B. Propellant Combination RFNA (14% NO_2, 1.5% H_2O)/80% UDMH-20% H_2O									
1.0	1.1138	0.2169	---	0.0004	2.2301	1.3624	1.0776	0.0009	6.7998
0.8	1.1955	0.2383	---	0.0437	2.7787	1.0408	1.1034	0.0034	6.3774
0.6	1.0766	0.2478	---	0.3427	2.7298	0.8822	1.1402	0.0056	6.3524
0.4	0.8466	0.2459	---	0.8110	2.3822	0.7969	1.1844	0.0067	6.5056
0.2	0.4562	0.2085	0.2449	1.3067	2.0198	0.8403	1.2419	0.0081	6.7111

C^* = Solid Carbon

$AAA = \frac{RT}{V}$

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